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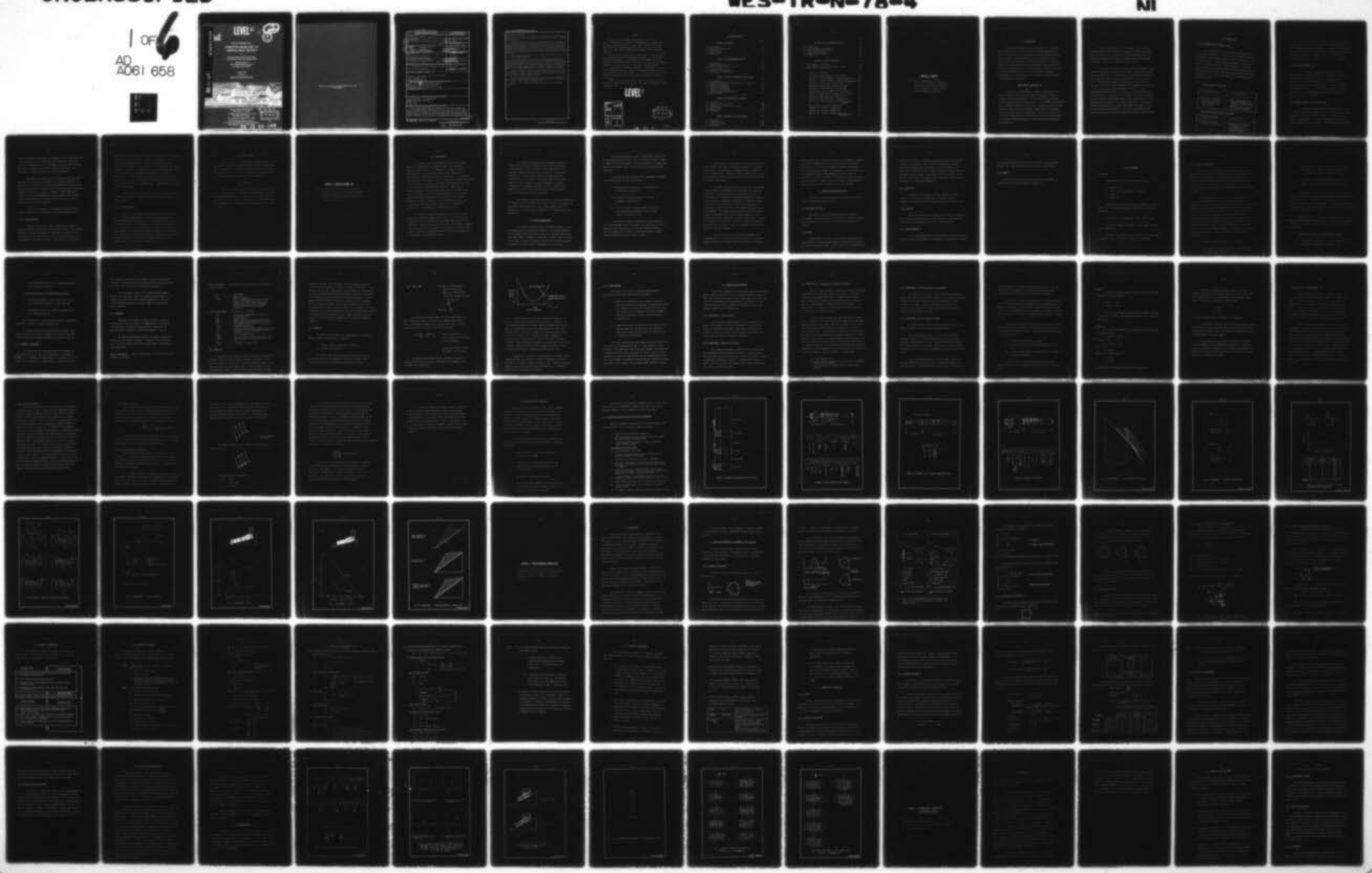

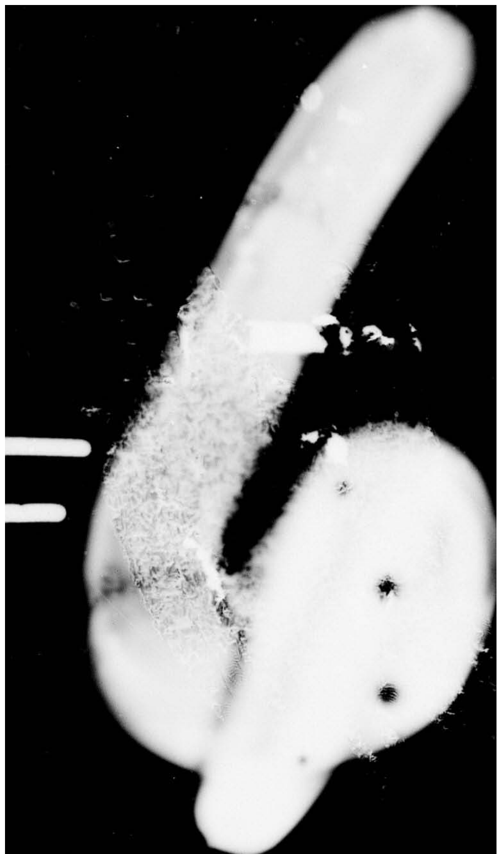

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TECHNICAL REPORT N-78-4

COMPUTER MODELLING OF JOINTED ROCK MASSES

by

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This report describes work that forms part of an effort to explain and predict the phenomenon of "block motion" which can occur in jointed rock when exposed to dynamic loading. The objectives of the study were to (a) evaluate a general method for modelling jointed rock; (b) translate the original Deformable Element Technique (DET) written in machine language into standard FORTRAN; (c) develop a method for allowing blocks to crack and break into separate elements; → next page

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20. ABSTRACT (Continued).

and (d) conduct a review of the behavior of rock joints and develop an improved constitutive law for rock block interactions. The major objectives of the study were achieved.

A numerical scheme for treating a fully deformable block was demonstrated to give accurate results. It was shown that very little error was introduced by the calculation of siding rock joints by the various rezoning schemes used. Although the new formulation is not likely to be more efficient than existing lagrange, finite difference codes, it was shown to have two major advantages; namely, it is completely general and can completely model any arbitrary jointing pattern and the joints are modeled accurately with no interpolation necessary at interface.

Other goals were accomplished. The original rigid block program was translated into FORTRAN Code, RBM.

A new idea for treating simple block deformability was developed. Each block was given three degrees of freedom to deform internally, with general constitutive laws given for the intact material. The method differs fundamentally from finite elements and finite differences in that it relies upon the stiffnesses of joints to link neighboring elements or zones. The new program, SDEM, is only slightly slower than the rigid block program and is useful in cases where the intact deformation of rock blocks is important but not large.

A modified version of the rigid block program, RBMC, was written which allow blocks to crack and divide into separate blocks in response to the loads acting on them. A simple cracking criterion was used which was based on empirical point-load tests on irregular blocks.

An extensive literature survey was made on the properties and behavior of rock joints. Based on these findings, a constitutive law was proposed for rock joints and coded into the subroutine JOINT.

Listings for all programs developed under this study are provided in appendices.

PREFACE

This report was prepared by Dames and Moore, Los Angeles, Calif., under Contract No. DACA39-77-C-0004 with the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. The work was jointly sponsored by the Defense Nuclear Agency and the Office, Chief of Engineers, U. S. Army, and was monitored by the Weapons Effects Laboratory (WEL), WES.

The studies were conducted by the Dames and Moore, Advanced Technology Group, and involved the following personnel: Dr. Peter Cundall, Principal Investigator; Dr. Joaquin Marti, Project Manager; Mr. Peter Beresford, Project Engineer; Mr. Nigel Last, Project Assistant; Ms. Margaret Asgian, Project Assistant; and Dr. Tidu Maini, Principal-in-Charge.

Contract Monitor for WES was Mr. James L. Drake of WEL. Dr. Eugene Sevin and MAJ Dave Spangler of DNA actively followed the progress of the contract and offered general guidance. Mr. Jerry S. Huie of the Soils and Pavements Laboratory, WES, managed the OCE program which supported part of this contract.

During the period of the contract, Director of WES was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown. Mr. William J. Flathau was Chief of WEL.

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CHAPTER 1: OVERVIEW

1.0 *The work described in this report is fitted into the context of the present state-of-the-art and the problems that need to be solved. A guide is given for the remainder of the report.*

1.1 INTRODUCTION

This report describes work that forms part of an effort by the Defense Nuclear Agency to explain and predict the phenomenon of "block motion" that can take place in underground structures exposed to strong dynamic loading. Large displacements across rock joints are known to have occurred during such events. These displacements at once pose great dangers to the structures, and present difficulties as far as analysis is concerned. Standard calculation methods that treat the rock as a continuum are clearly inappropriate, but it is not always easy to incorporate discontinuities in a realistic way, and to prevent the computer programs from becoming large and unwieldy.

1.2 HISTORICAL PERSPECTIVE

Lagrangian, finite-difference programs are widely used in the Defense Community, and have evolved from pure hydrodynamics codes by utilizing a non-zero shear modulus. Yield and failure can be modelled, but the formulation remains essentially that of a continuum. Discontinuities may be incorporated by means of slide-lines, a technique that was described by Wilkins (1969); however the procedure becomes difficult and expensive when multiple joint sets must be represented. Part of the reason for this is that the formulation has evolved historically from a continuum approach that has been successively modified to treat greater and greater degrees of discontinuity.

Perhaps it would be better to work the other way: to introduce continuum behaviour into a method that is designed to model only discontinuities. It may turn out, of course, that the two approaches will lead to essentially the same final formulation, in which case nothing would have been gained. However it was thought to be worth a try.

The starting point was the distinct element method (DEM) that was originally proposed in a restricted form by Cundall (1971) and generalised later on (Cundall, 1974). It was developed for low-stress rock situations, where displacements due to joints far exceed those of the intact rock blocks. The simplifying assumption was made that the intact rock was rigid, and that only the joints could deform. The method works explicitly in time, and permits large block movements and rotations. A novel housekeeping scheme keeps track of all blocks in an efficient manner, and allows any block to interact with any other block. The notion of treating blocks as rigid was also pursued by several other workers, using the finite element method (e.g. Burman (1971), Chappel (1972, 1974)). However these formulations were restricted to small displacements, and used an implicit solution method, which brings with it a whole host of difficulties when modelling problems that have strong geometrical or material non-linearities.

1.3 PRESENT WORK

1.3.1 DEFORMABLE-BLOCK PROGRAM - DBLOCK

As its main topic, this report presents an evaluation of a general method for modelling jointed rock. In contrast to the updated hydrodynamics codes referred to above, the new work regards the joints and discontinuities as the most important components, and throws the burden of approximation onto the continuum formulation. As blocks slide over one another and make and break contact, continuum zones are created, deleted and re-zoned. The errors associated with this process are evaluated in this report. To summarize, the two approaches may be compared as follows:

New deformable-block program:

Continuum Formulation	Joint Formulation
• Subject to error due to re-zoning - triangular zones created, deleted and modified due to contact changes.	• More or less exact - the force/displacement law is used directly between grid-points; • Arbitrary block complexity is treated as standard.

Traditional Lagrangian code - e.g. HEMP:

Continuum Formulation	Joint Formulation
• No significant errors introduced by slide-lines.	• Subject to error due to interpolation necessary on slide-lines; • Only simple interaction geometry possible.

The deformable-block program, DBLOCK developed here is simply a "test-bed" code to prove and demonstrate the proposed formulation. It is not intended to be used to run complex problems, since the housekeeping logic used by Cundall (1974) has not yet been incorporated in the program. This will be the subject of a further contract, if the method proves successful. The point will be taken up again in the final chapter.

1.3.2 RIGID-BLOCK PROGRAM - RBM

Since the original program written by Cundall (1974) was partially written in machine language, part of the present contract was concerned with translating the machine language program into Fortran. The resulting program, RBM, is to be regarded as a "base-line" program that can be used by interested parties as a base on which more complex codes can be built. For this reason the program has been kept deliberately free of embellishments and complexities that would tend to obscure the workings of the program.

1.3.3 SIMPLY-DEFORMABLE BLOCK PROGRAM - SDEM

The general deformable block program (Section 1.3.1) is likely to be complex and possibly as expensive to run as regular HEMP-type codes, although it is anticipated that the results for jointed media will be superior. Such an approach is clearly necessary when each rock block deforms internally in a complex manner. Complex deformation implies many

degrees of freedom, which can only be represented by internal discretization or multi-noded zones (as in higher order finite elements). Multi-noded zones are not desirable in an explicit scheme as each zone must be treated implicitly. We appear to be stuck with internal discretization if we really need to represent complex modes of intact deformation.

There may by an argument for trying a simpler approach for those problems where internal block deformation is of secondary importance, but still has to be accounted for. This line of development has led to program SDEM, which is basically an enhanced version of the rigid-block program, RBM. SDEM gives each block three degrees of freedom to deform internally, in addition to the three rigid-body modes already associated with each block in RBM. The formulation is for large strains, and can use any form of constitutive law, such as plasticity.

The program gives the user a good deal more realism for intact behaviour, without too much degradation in efficiency compared to RBM.

1.3.4 CRACK FORMULATION

Although it is extremely complex computationally to model the complete mechanics of crack propagation accurately in rock, it was considered worthwhile to modify program RBM so that any block could split into two as a function of the loads applied to it and utilize semi-empirical laws to determine when the block would crack. There is quite a large body of

experimental data that enables crude estimates to be made of the point-contact loads that will cause rock blocks of given sizes and shapes to crack. In this way the program would be given added realism without sacrificing efficiency by too much. In many situations it is expected that the progressive movements in a rock mass are insensitive to the exact fracture loads, so long as the fractures do occur. Without any possibility of cracking, the behaviour can be most unrealistic, with corners "locking-up" even though the overlap is very small. When blocks are allowed to crack, the criterion for cracking may be varied in parameter studies to determine what effect it has on overall behaviour.

Chapter 4 describes the modifications necessary to RBM in order to allow cracking to occur. Suggestions are made concerning the choice of crack criterion.

1.3.5 JOINT FORMULATION

Whichever of the approaches described above is selected to model real situations, a constitutive law is needed to represent rock joints. The formulation should be general enough to accomodate the whole spectrum of observed behaviour. To this end, a literature survey has been made of field and laboratory tests on jointed rock. A summary of the findings is given in Chapter 5, together with a suggested framework for a constitutive law. A few tests have been made using this law in conjunction with program DBLOCK, but many more tests are anticipated when simulations of real events are made in the next phase of the work.

1.4 LAYOUT OF REPORT

Each of the topics discussed above is treated in detail in its own chapter. The figures for each chapter are collected together at the end of the chapter, but references are "global" and appear in Appendix I. Each chapter is more or less self-contained, with an introduction and conclusion, but global conclusions are presented in Chapter 7.

1.5 CONCLUSION

The work described in this report should be regarded as open-ended. Several approaches to the problem of modelling block motion have been investigated, with a view to using one or all of them in the next phase, which will be to simulate actual events, and compare predictions with measurements. The discussion of future possibilities will be left for Chapter 7.

CHAPTER 2: BASELINE PROGRAM, RBM

2.0 *The original distinct element program developed by Cundall (1974) was written in machine language. This chapter describes the translation of that program into Fortran. Examples, validations and a users' guide are given.*

2.1 INTRODUCTION

The original, general implementation of the distinct element method was a program written in machine language, and described in a report by Cundall (1974). It is assumed that the reader is familiar with that report, since it has been followed almost exactly in the Fortran version of the program described in this section. Few departures have been made from the original logic even though many potential improvements could be envisaged. This was in line with the philosophy that the Fortran program should be a "baseline program": that is, a simple, easily-understood program to form a base from which other, more flexible codes could evolve Section 2.6 contains several suggestions for improvements. Some of these have already been incorporated into the program SDEM, described in Chapter 3. Almost all of the improvements are built into another program, BALL, which models the mechanics of assemblies of circular discs. This program is described by Cundall (1978).

The baseline program, RBM (described in this section) models assemblies of arbitrary, angular blocks. There is no restriction, apart from memory limits, on the geometry, displacements and rotations of the rock blocks. Any block may touch any other block. The response to imposed forces and constraints is calculated using an explicit integration scheme, thereby allowing large displacements and general force/displacement laws to be handled in a straightforward manner.

The original program was written in assembly language for a computer with an interactive graphics display. This note describes an implementation of the calculation section of the program in a high level language; the program was not written for an interactive display, but it contains simple routines for drawing blocks on a standard plotter (e.g. Calcomp). The approach taken in writing the program was that it should be as machine-independent as possible. Consequently it is somewhat inefficient in its use of memory: for example whole (32-bit) words have been used for flags, which were stored as single bits in the original program.

The following sections have some notes on the Fortran implementation, the departures from the original logic, notes on the use of the program and some examples and validations. A list of input commands is given in Appendix III, a subroutine guide in Appendix IV and a program listing in Appendix XII.

2.2 FORTRAN IMPLEMENTATION

The original program was written in assembly language for a small minicomputer with no floating point processor. A Fortran implementation on that computer would have been very slow to run, and would have allowed only a small number of blocks to be modelled. In order to make the program more portable, it has been rewritten in Fortran, and it should be possible to implement it on most computer systems with little difficulty.

The original program was written in three phases, the first two for describing the model, and the third for allowing the blocks to respond to imposed forces and constraints. This Fortran version is concerned with the third (calculation) phase, and the input has deliberately been kept rudimentary.

In order to make the program as machine independent as possible, the following conventions have been observed:

(i) Word lengths are identical (i.e. integer and real variables are the same size).

(ii) Only four characters are stored in a word for alphanumeric representation.

(iii) Input and output is standard sequential access, for both formatted and unformatted files, and output formats use Hollerith strings.

The allocation of memory is performed in a manner similar to the original program, with all the linked list arrays stored in a single memory partition, the allocation of this memory depending upon the particular problem being analysed. In this way no storage is wasted. A map of this memory partition is shown in Figure 2.1.

The data arrays for the blocks, the box array and corner list, and the contact array and list are shown in Figures 2.2, 2.3 and 2.4 respectively. As noted earlier, each member of these arrays uses a single storage location. Substantial storage economies can be effected on installations allowing variable length words, but this practice was deliberately avoided here.

The original program was written for use with a CRT (cathode ray tube) display, and depended heavily upon this for its input and output (I/O). The present program was written specifically for a system without this capability, the primary purpose being to implement the data structures and physical algorithms in a high level language, and to leave the I/O to the user. In any case, sophisticated I/O is governed by the machine being used, not to mention the preferences of the programmer. The present program requires the user to describe his problem in card image format (the data input description is given in Appendix III) and the primary form of output is the pen plot (a snapshot of the problem at a given time). An echo of the data input stream is produced on the line printer, as well as the capability of printing the data lists and other information.

It is very easy to write an inefficient FORTRAN program, especially when it is essentially iterative in nature. The algorithm employed in the present program involves many thousands of timesteps,

and the computing time is directly proportional to the number of timesteps. Any savings in computer time effected in the iteration cycle would be very beneficial. To this end, the number of arguments in subroutine calls has been kept to a minimum. As a consequence of this practice, and of the petty restriction in ANSI FORTRAN that variables cannot be equivalenced to subroutine arguments, the program is a little less easy to read than it might be. However, reading the listing in conjunction with the data structure diagrams eliminates most of the obfuscation.

2.3 DEPARTURES FROM ORIGINAL LOGIC

This section describes the differences between the logic of the original program and the Fortran version.

2.3.1 NEW ENTRIES TO LISTS

New entries to lists are appended rather than inserted at the beginning. This was done purely for convenience, since the variables associated with the end of the list are available when extension is required.

2.3.2 UPDAT

Routine UPDAT is no longer called at regular intervals, but an algorithm has been implemented that automatically requests the updating of the contact lists when necessary. At each timestep, the maximum magnitude

of all block velocities is determined and integrated to give a fictitious increment in displacement. These displacement increments are summed, producing a maximum possible displacement since the last update. This displacement is usually fictitious. When it exceeds the specified tolerance, the update routine is called. The advantage of this algorithm is that UPDAT is called frequently at times of rapid motion, but is seldom called when the model is approaching equilibrium.

2.3.3 EMPTY LIST

The empty list, containing all unused contacts is initially created to the end of the available memory, so that the concept of additional storage, after this list has been exhausted, is no longer valid.

2.3.4 FIX FLAG

When a fixed block has been plotted, its "fix flag" is incremented by 2 so it will not be plotted again. This modification was made because of the relatively slow speed of pen plotting compared with CRT.

2.3.5 DRIFT CORRECTION

Due to the higher precision of the arithmetic in the Fortran version, the drift correction was assumed to be unnecessary, and was omitted. However

if a corner penetrates more than one unit into an edge, a warning message is printed out. This usually means that the program is being mis-used.

2.3.6 DAMPING

Both mass-proportional and stiffness-proportional damping are available, and are discussed in detail in Section 2.4.6.

2.4 USE OF PROGRAM

2.4.1 FILES

The following logical units are used by the program:

1. Restart file

(3) Plot file (only used in PDP 11/45 version)

5. Input file

6. Output file

The Restart file is written by the program whenever it stops normally, and is used when the program is started again to restart from the same point.

The Plot file is written whenever a PLOT command is given.

Logical Unit 5 expects a sequence of input commands; these are given in Appendix III.

The printer output appears on Logical Unit 6. All input commands are echoed on output, so that Unit 6 serves as a logging device.

2.4.2 CHOICE OF COORDINATES

The present version of RBM does not allow the user to choose an arbitrary coordinate space, for reasons that will be outlined below. This means that a problem posed in an unacceptable coordinate system must be transformed before using RBM, and the results transformed back again after the run. Suitable transformation logic could easily be built into RBM if desired, but has not been done so in order to keep the program as simple as possible.

Both reboxing and contact searching are triggered by blocks crossing integer boundaries. That is to say, when the integer part of either the x- or the y- coordinate of a block centroid changes, the routine REBOX is called for that block. REBOX determines whether the box entries for the block are correct, and if they are not, it creates and deletes entries as necessary. UPDAT, which is also triggered by an integer boundary being crossed, creates new contacts if they should exist but do not. The utilization of the integer parts of the coordinates to initiate reboxing and updating clearly limits the coordinate ranges that can be used, but a good deal of memory is thereby saved; otherwise old coordinates would have to be stored in order that cumulative movements could be calculated.

The following restrictions apply to the use of RBM:

i) The coordinate origin forms the lower, left-hand point of the problem space (box area).

ii) Block dimensions should be in the order of 10 to 100 coordinate units. Dimensions outside these limits can be used, but the user should know what he is doing.

iii) The number of boxes should be between 1 and 1/10 of the number of blocks in the problem, with a minimum of, say 16.

Before running a problem, the box area must be chosen. This area should be slightly larger than the greatest anticipated area that the system of blocks will require. At present, the program automatically fixes a block if it tries to move outside the box area. A suitable number of boxes to cover the box area should then be chosen, bearing in mind the considerations given above. Blocks may then be created.

Although the choice of coordinates should have no effect on the physics, it will influence the efficiency of the program, which will depend on the sizes of the blocks expressed as integers. The following effects may be noted:

Large numerical values of block dimensions will give:

1. minimum memory requirements, since contact space will only be allocated for particles that are very close;

2. increased computation time, since reboxing and updating will be done very frequently.

Small numerical values of block dimensions will give:

1. high memory requirements, since contact space will be retained when blocks separate to large distances;

2. low computation time, since reboxing and updating will be triggered infrequently.

For a problem that is critical in time or storage, experiments can be made to determine an optimum coordinate range.

The number of boxes also influences speed and storage. Many boxes will increase the storage requirements, but decrease search time; few boxes will decrease storage requirements, but increase search time.

2.4.3 SEQUENCE OF OPERATIONS

The commands given to the program (described in Appendix III) are divided into two sets. The first command must be either START or RESTART. If it is RESTART, the program reads an existing restart file and jumps to data set number two. A START command, on the other hand, must

be followed by a specification of the number of blocks in the problem, the number of boxes and their sizes and the fraction of critical time-step to be used. Data set two may then be given to the program.

The program RBM is similar to the original machine language version in that the set of blocks, once created, cannot be added to. In practice this means that no further CREATE commands may be given after a CYCLE command has been used. All other commands in set two may be given at any time.

2.4.4 PRINTOUT

Each input line is echoed on output, followed in some cases by an informative or error message. The CREATE command is followed by the coordinates of the block that have been read, together with the computed centroid coordinates, the mass and the moment of inertia.

The DUMP command produces, initially, a summary of the program pointers and other internal variables. On request, it will follow this with a list of box entries, block data and contact data. These printouts are explained below:

2.4.4.1 Box entries: These are simply given as a list of block corners that map into each box.

2.4.4.2 Block data: The headings are self-explanatory, except perhaps for the following:

NB . . .	block number
IF . . .	"fix" flag
NC . . .	number of corners
THETA . .	this is the angle that the block has moved through since THETA was last set to zero. THETA is set to zero when its magnitude exceeds 0.01 radians. The actual angle can be deduced from the COS and SIN printouts.

2.4.4.3 Contact data: The symbols are as follows:

NBE . . .	block number corresponding to the edge of the edge/corner pair
PRE . . .	preserve flag
NPE . . .	number of the edge involved in the contact
NPC . . .	number of the corner involved in the contact
NBC . . .	block number corresponding to the corner of the edge/corner pair
LINK . . .	pointer to next contact
S, N . . .	not used at present, but intended for storing comulative shear and normal displacements, if required for a non-linear law.
FN, FS . . .	normal and shear forces
SIN, COS . . .	sine and cosine of the angle of edge (of the edge/corner pair) to the global x-axis of the run
XCP, YCP . . .	coordinates of contact point.

2.4.5 TIME-STEP

With any explicit program, the critical time-step is determined by the highest eigenvalue (highest natural frequency) in the system. If the time-step is made larger than critical, numerical instability results. This form of instability is usually obvious when it occurs, but may be masked if mass-proportional damping is used or energy is being dissipated by sliding.

If there is any doubt about the results, the run should be repeated with lower time-step and the results compared. The program calculates a critical time-step, but one that is based only on the oscillation of a single degree-of-freedom system with the lowest mass and highest stiffness in the problem. The user must reduce this time-step still further by specifying a fraction (FRAC) by which the computed time-step is multiplied. This is necessary because the apparent stiffness acting on a block increases as it becomes surrounded by other blocks. A value of FRAC of 0.1 is probably safe for most problems, but 0.2 to 0.5 may be used with caution for loosely-packed assemblies. If stiffness-proportional damping is used, a lower time-step is needed for stability, but mass-proportional damping does not influence the numerical stability.

2.4.6 DAMPING

Two forms of viscous damping are incorporated into the formulation embodied in RBM. Physically these correspond to:

a) dashpots from block centroids to "ground";

b) dashpots across contacts.

The dashpots across the contacts operate both in the shear and normal directions; the shear dashpot is "switched off" during sliding. In finite-element notation, the damping is described as follows:

$[c] = \alpha[m] + \beta[k]$ where $[c]$ is the damping matrix

$[m]$ is the mass matrix

$[k]$ is the stiffness matrix

α and β are constants, given by

$\alpha = \lambda_{min}\ \omega_{min}$ and

$$\beta = \frac{\lambda_{min}}{\omega_{min}}$$

where $f_{min} = \frac{\omega_{min}}{2\pi}$

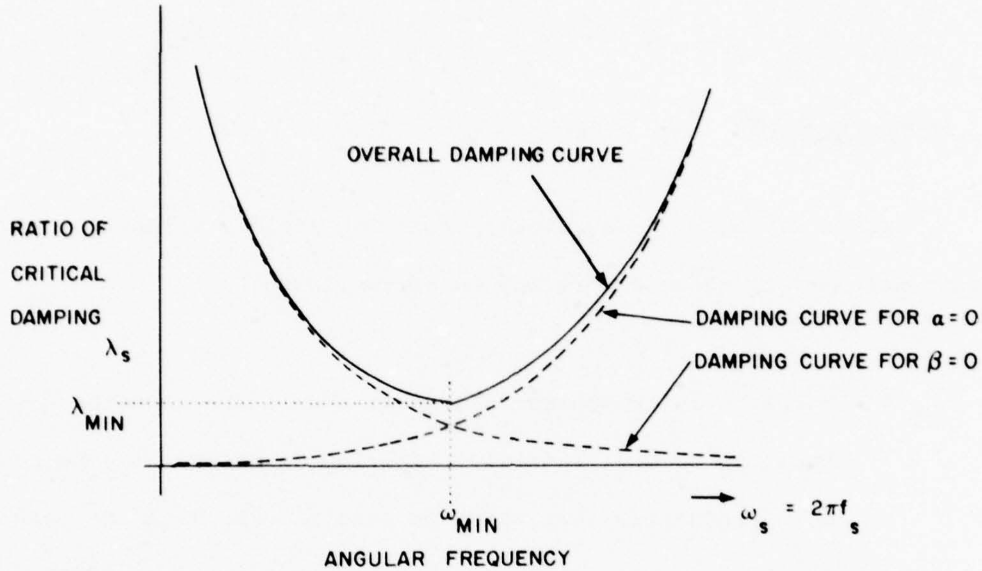
For an elastic continuous system (i.e. one in which there is no slip or breaking and making of contacts), the damping scheme described above is termed Rayleigh damping (e.g. see Seed *et al*., 1970). It damps the natural modes of oscillation of the system as follows:

$$\lambda_s = \frac{1}{2}\left(\frac{\omega_s}{\omega_{min}} + \frac{\omega_{min}}{\omega_s}\right)\lambda_{min}$$

where λ_s is the fraction of critical damping for mode s with angular frequency ω_s.

ω_{min}, λ_{min} are input parameters described on the plot below.

The equation given above shows that the damping varies with frequency, and in particular there is a minimum value for damping. This is shown in the following plot:



As remarked earlier, the theory reported above applies to an elastic, continuous system, which has natural modes of oscillation. For a discontinuous system that dissipates energy in slip the theory does not apply, but damping still occurs, and can be understood in terms of the physical effects of each type of dashpot. The mass-proportional damping has an effect similar to that of immersing the block assembly in a viscous fluid; i.e. absolute motion relative to the frame of reference is damped. Stiffness-proportional damping on the other hand is equivalent to dashpots connected across the contact stiffnesses (springs); in this case block-to-block motion is damped, but absolute motion is not.

Either type of damping can be used separately or together. Mass-proportional damping is effective in reducing low frequency motion where the whole block assembly "sloshes" from side to side. Stiffness-proportional damping is more effective against the high-frequency noise of individual blocks "rattling" against their neighbours.

2.4.7 KNOWN PROBLEMS

Errors may occur if a block is rotating rapidly without translational motion; these errors may be of two forms:

i) Reboxing is triggered only after cumulative rotation has built up to 0.01 radians. Reboxing of corners may be needed more frequently than this for long blocks, with the result that, either an error message will be printed by REBOX, or UPDAT will fail to find a contact, and allow blocks to interpenetrate.

ii) Updating of contacts is triggered only on cumulative translational motion, so that new contacts may be missed for blocks that are only rotating. Again, the effect will be for blocks to interpenetrate.

The errors described above are unlikely to occur for normal runs. If they do, it will be immediately obvious - either blocks will interpenetrate, or the program will halt with an error message. The problem may be overcome by storing global coordinates for corners, instead of local coordinates. Updating and reboxing could then be triggered directly from true corner movements, regardless of whether they were caused by translation or rotation. Such a scheme is used in program SDEM, described in Chapter 3.

2.5 EXAMPLES AND VALIDATIONS

This section documents some of the validation runs that have been made with RBM to verify that it works as intended. During the course of these tests some bugs were found, and some changes made to the pre-release version of the program that was made available in September 1977. For completeness these changes are documented in Appendix IV; the current version of RBM is listed in Appendix XII.

2.5.1 VALIDATION 1 - Block on plane

This qualitative example illustrates a block sliding down a plane. The coefficient of friction is firstly set so that the block accelerates under gravity, secondly to bring the block to rest, then thirdly to allow it to accelerate again and topple off the edge of the plane. This final event is illustrated in Figure 2.5.

2.5.2 VALIDATION 2 - Impact of two blocks

This example was intended to check for symmetry during impact, when two identical blocks are allowed to collide. It is worth noting that the contact forces are transmitted at the block corners only. Energy and momentum are conserved, and there is no angular motion after the impact, even in the extreme case of point-to-point contact in the second run. Figure 2.6 shows the results.

2.5.3 VALIDATION 3 - Conservation of energy and momentum

Figure 2.7 shows the effect of varying the timestep on the energy and momentum after the eccentric impact of two blocks. The kinetic energy and total momentum after impact are compared with the initial values, and the kinetic energy is plotted against fraction of critical timestep. Linear momentum is conserved exactly in all examples. It is observed that total momentum is conserved, and that kinetic energy is conserved as the timestep tends to zero.

The reason kinetic energy is not conserved exactly for higher values of timestep is that the program does not compute exactly the time of making or breaking of the contact. When the two blocks come into contact, the resulting mass/spring system starts to execute part of a cycle of simple harmonic motion. Theoretically, the release of the contact should occur when the force between the two blocks passes through zero. However this will not be the case if an integral number of time-steps does not fit into half a cycle of oscillation, since the release time is only taken to the nearest time-step, Δt. It is quite simple to overcome this inaccuracy by employing logic that determines the exact release time, and interpolates the force accordingly. This was not done, for several reasons:

a) to save computing time;

b) Δt would be small anyway, due to the constraints imposed by a dense packing of blocks;

c) the program would not generally be used to model impact problems.

2.5.4 VALIDATION 4 - Blocks falling into a receptacle

The object of this test was to check the reboxing and updating logic for multiple blocks and complex interactions. The example illustrates a number of blocks being allowed to fall under gravity into a fixed receptacle, and coming to rest where they have fallen (Figure 2.8). Inspection of the contact and box lists using the DUMP command showed that the logic was working as intended.

2.5.5 VALIDATION 5 - Block falling onto plane

The object of this test was to verify that the accelerations and decelerations both in free fall and in sliding were correct.

The initial conditions (time $t = 0$) for this validation are presented in Figure 2.9. The coefficient of friction (μ) was chosen to be slightly greater than tan α so that the free block would be retarded after it started sliding on the plane. The fraction of critical time-step was taken to be 0.1, in view of the considerations presented in the previous section.

Since the problem was basically one of a dynamic nature, the important damping effects were those due to stiffness damping and so the mass damping term of the Rayleigh equation was suppressed. The fraction of

critical damping at the minimum frequency f was taken as 0.5, and f was calculated as the frequency of the single degree-of-freedom system comprising the mass of the block and a single contact stiffness.

Validation 5 (case A) was run from time $t = 0$ with the position of the free block being plotted and numerical data being obtained after two periods of 500 cycles. The block was then just above the inclined plane; after this it was necessary to reduce the periods to 100 cycles in order to observe the details of the motion. Graphical output is presented in Figure 2.10(a).

Figure 2.10(b) shows the variation of the velocities in the x and y directions with time, from which it is evident that after 2,500 cycles the accelerations have become constant. The falling block has been through three distinct stages:

i) constant acceleration due to gravity;
ii) an impact resulting in the block toppling over onto one side;
iii) constant retardation due to the effect of friction between the block and the plane.

Stages i) and iii) can be examined analytically since they represent simple motion in a straight line under the effects of constant forces.

Stage i)

For a free falling body with zero initial velocity the following equations of motion can be applied:

velocity, $v = gt$

distance, $s = \frac{1}{2}gt^2$

For a time t represented by 1,000 cycles those equations predict $v = -62.04$ and $S = -196.20$. The program gives values of -62.0 and -196.0 respectively.

Stage iii)

For a body sliding down a rough inclined plane under the action of a constant force P

$$P + \mu mg \text{ Cos } \alpha - mg\text{Sin}\alpha = 0$$

and since $p = ma$

$$a = g (\sin \alpha - \mu\cos\alpha).$$

For $\mu = 0.30$,

$$a = -0.476$$

And in the coordinate directions

$$a_x = 0.461$$

$$a_y = 0.115$$

The program indicates values of 0.459 and 0.114 respectively.

The run was repeated with a higher coefficient of friction (case B) and the results are shown in Figures 2.11(a) and 2.11(b). With this slightly higher value the block comes to rest while still on the plane. For this case the theoretical predictions are:

$$a_x = 0.922$$

$$a_y = 0.231$$

The program indicates values of 0.919 and 0.231 respectively.

An examination of the contact forces reveals the expected results. The condition $FS = \mu FN$ is maintained almost exactly as the block slides down the plane and comes to rest. The forces on the stationary free block are those predicted from static theory.

The conclusion to be drawn from this validation is that the friction formulation and the MOTION subroutine appear to be functioning correctly. Any small discrepancies in the numerical data probably result from the fact that the free block undergoes small oscillations about its centroid as it travels down the plane.

2.5.6 VALIDATION 6 : TOPPLING BLOCKS

Goodman and Bray (1976) present an analysis of a system of toppling blocks using limiting equilibrium methods. They analyse the system of blocks shown in Figure 2.12(a). For various values of the coefficient of friction, the analysis gives the magnitude of the toe force, T, necessary for the system to be just on the point of collapse. The mode of failure is also predicted: in the case illustrated, the three upper blocks remain stable, the lower four blocks slide on the base, and the remaining nine blocks rotate about their lower corners.

Figure 2.12(b) shows the system of blocks as set up for the run with RBM. The dimensions of the blocks were ten times those used by Goodman and Bray (G&B) in order that contacts would be detected within a small fraction of the block dimensions. Consequently block weights and forces were one hundred times those used by G&B. Two runs were made: the first was to determine the coefficient of friction required for the blocks to be stable with T=O i.e. zero toe force . The second run was for a coefficient of friction of 0.65; the object was to determine the magnitude of the force, T, for limiting equilibrium. For interest, Figure 2.12(c) shows a plot from RBM with the coefficient of friction equal to 0.65, but with zero toe force: the blocks are in the process of failing.

2.5.6.1 Run 1, Validation 6

For this run the load, T, was set to zero and the coefficient of friction varied, in order to bracket the value required for stability. Initially, however, the system of blocks was "compacted" by allowing gravity to act for some time along the long dimension of the blocks. Gravity was then rotated to the correct direction for the stability test. For the initial compaction, the mass damping (see DAMPING command in Appendix III) was set to 0.5,0.7,0,1. The damping was then reduced to 0.05, 0.7,0,1 for the subsequent test of stability. Two different friction values were used for the stability test, which consisted of two restart runs, both starting from the same restart file created at the end of the compaction stage. The predicted coefficient of friction for limiting equilibrium was 0.7855. For a value of 0.80 the system of blocks moved slightly and then stabilised, as judged by the velocities reducing to low values and the out-of-balance forces and moments on block centroids tending to zero. However for a friction coefficient of 0.77, the blocks continued moving, with the velocities increasing. It was noted that the mode of failure was slightly different from that predicted by Goodman and Bray, in that only three of the lower blocks were sliding rather than toppling, compared to four blocks predicted by Goodman and Bray.

2.5.6.2 Run 2, Validation 6

For this run the friction coefficient was held constant at 0.65, and the load, T, varied in order to determine the value required for stability. As for Run 1, the various tests were made from a common starting-point, using the restart file created at the end of the compaction phase. The damping parameters for the stability tests were:

$$\begin{cases} \lambda_{min} = 0.25 \\ f_{min} = 0.7, \text{ with the stiffness term set to zero.} \end{cases}$$

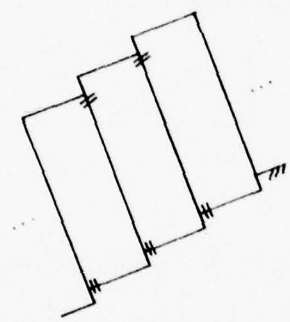
Goodman and Bray predict the critical value of T to be 2013 units, but the system was found to stabilise with T=2000 units. At T = 1900 units the blocks were definitely unstable, and collapse occurred.

2.5.6.3 Conclusions from Validation 6

Run 1 bracketted the coefficient of friction with a range that includes the value predicted by Goodman and Bray. However Run 2 showed that the system of blocks was stable for a lower value of toe force than predicted. Although the difference was quite small, it is worth trying to understand what caused it.

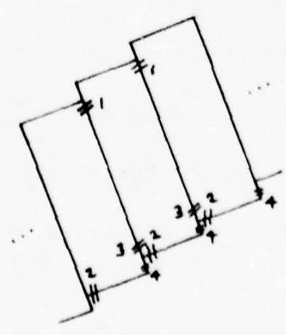
For T = 2000, RBM found a valid system of forces that satisfied equilibrium. Since this corresponds to the requirements for a lower bound solution, the observed force, T, should have been higher than the "true" value for limiting equilibrium, rather than lower. A check was made by

hand that the forces acting on individual blocks did indeed sum to zero. The reason for the discrepancy was traced to the fact that the system of contacts assumed in Goodman and Bray's analysis differed from that developed during the computer run with RBM. For the toppling blocks, Goodman and Bray assumed the contacts to be located as shown below:



// = contact between
two blocks.

The contacts observed to have formed at equilibrium in Run 2 were as follows:



The magnitudes of the forces were:

1 and 2 ... high

3 ... quite high

4 ... very low

It was conjectured that the different location of the forces was responsible for the greater apparent stability of the system of blocks. In particular the effect of the two forces acting on the long edge of each block would be equivalent to a single resultant force acting some way down the edge, and not at the top, as assumed by Goodman and Bray. In order to test the conjecture, a program was written that carried out a Goodman and Bray limit equilibrium analysis, but with a variable contact location on the long edges, rather than fixed at the top. A variable, C, which could take values between 0 and 1, specified the location of the contact point as a fraction of the block height. All blocks were affected by the change, with a value of 1.0 for C giving the standard Goodman and Bray solution. However, moving the contact points down gave the following reductions in the force, T, necessary for stability:

C	T	
1.0	2013	(standard result)
0.75	1995	
0.50	1902	

Both the direction and magnitude of the change in T correspond well with the experience with RBM (Run 2) reported earlier. Although this result lends support to the conjecture that changes in contact locations are responsible for the changes in stability, it is not the whole story, since the contact locations can also vary on the lower edges and they can also be different for different blocks.

It is not clear whether the assumptions made by Goodman and Bray are any more realistic than those implicit in the distinct element simulation. Finite rotations must occur before the contact points migrate to the top corners of the toppling blocks, but these cannot occur until the system starts to fail. It would appear that the force necessary to prevent any movement is smaller than the force necessary to restore equilibrium, once a very small movement has occurred.

2.6 CONCLUSIONS AND SUGGESTIONS

Almost a one-for-one translation of the original assembly-language distinct element program into Fortran has been made. The temptation to "improve" the program has been resisted, because the program is intended to serve as a base-line version from which more exotic versions can be developed. Its use of memory could certainly be improved, and perhaps its speed as well; these points are addressed below. However it has been established by several validations that the program works as intended.

It should perhaps be recorded that certain constraints in the original assembly language version are not present in the Fortran version, RBM:

1) Block velocities can assume any value; there is no limiting velocity in RBM.

2) Inertial masses have the correct physical values (recall that all blocks had the same mass in the original program).

3) The moments of inertia are also correct.

4) The timestep in RBM corresponds to real, physical time (in the original program the apparent time-scale was different for different-sized blocks).

The constraints of the original program were due to the fact that variables had to be represented as integers, which limited the range of permissible numbers. Of course RBM does not suffer in this way.

2.6.1 SUGGESTIONS FOR FUTURE MODIFICATION AND DEVELOPMENT

Many of the suggested developments have already been made to the following programs, all of which work on similar principles:

1) SDEM, the program described in Chapter 3;

2) BALL, the program developed by Cundall (1978) for research into the mechanics of granular media;

3) a new program under development to allow the discrete blocks of SDEM to crack.

The suggestions are as follows:

1) Free-format input (as in SDEM).

2) Coordinate transformations built-in, so that any set of problem coordinates could be used.

3) Allow blocks to be created at any time. (see BALL)

4) Use global coordinates for block corners instead of local; this will allow reboxing to be more efficient and foolproof (see SDEM).

5) Store box entries all along block edge, rather than just for corners (see BALL). This will allow local (single block) updates, rather than the present global updates.

6) Eliminate storage of non-essential variables - e.g. edge lengths, block angle, COS , SIN of block, force-sums on block.

7) Allow different properties for different joints and blocks.

8) Incorporate edge-to-edge contact formulation for almost-parallel edges.

9) Incorporate cracking, joint water pressure and dynamic loading.

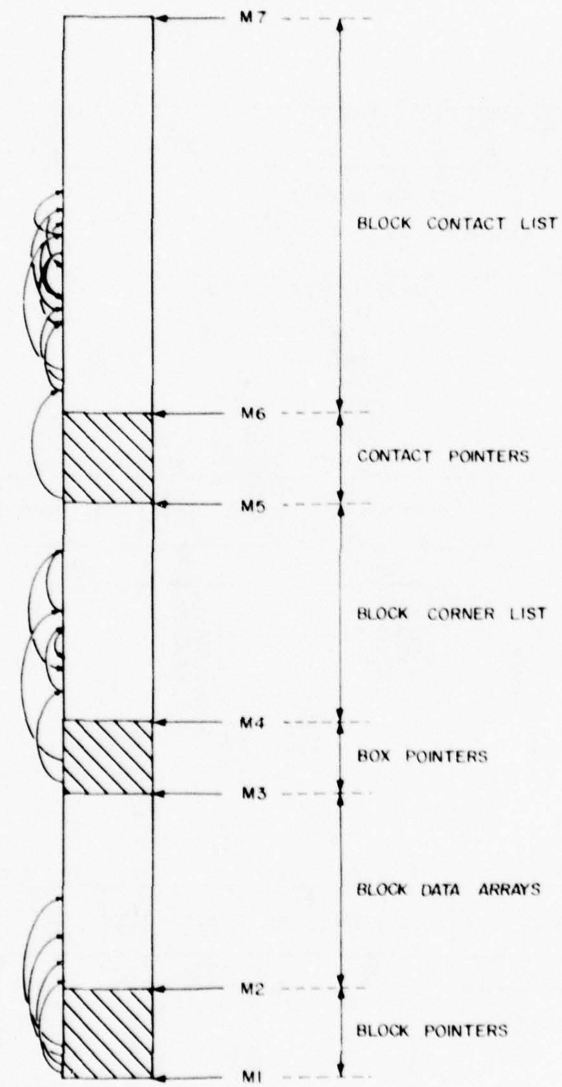


FIGURE 2.1 MEMORY ALLOCATION FOR DATA LISTS

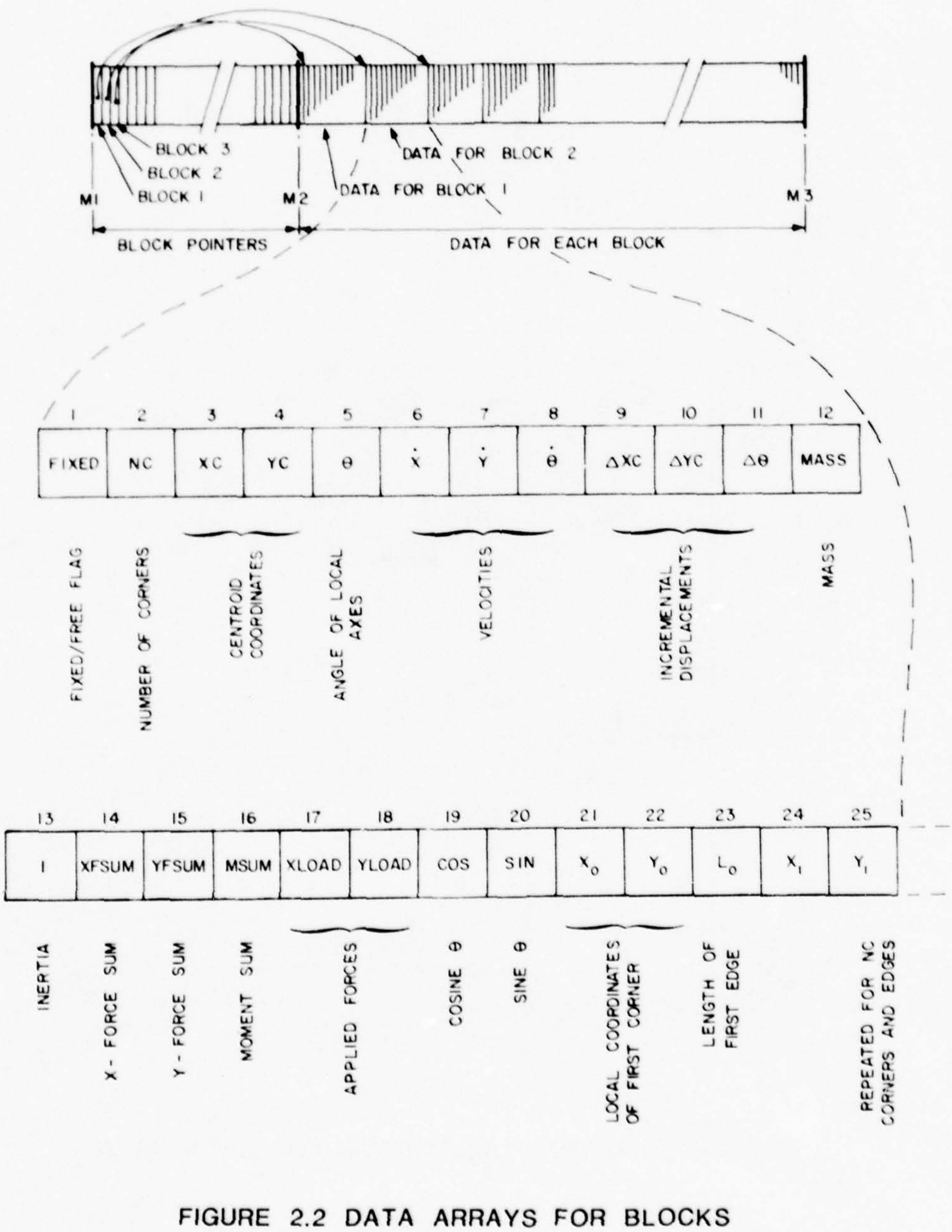


FIGURE 2.2 DATA ARRAYS FOR BLOCKS

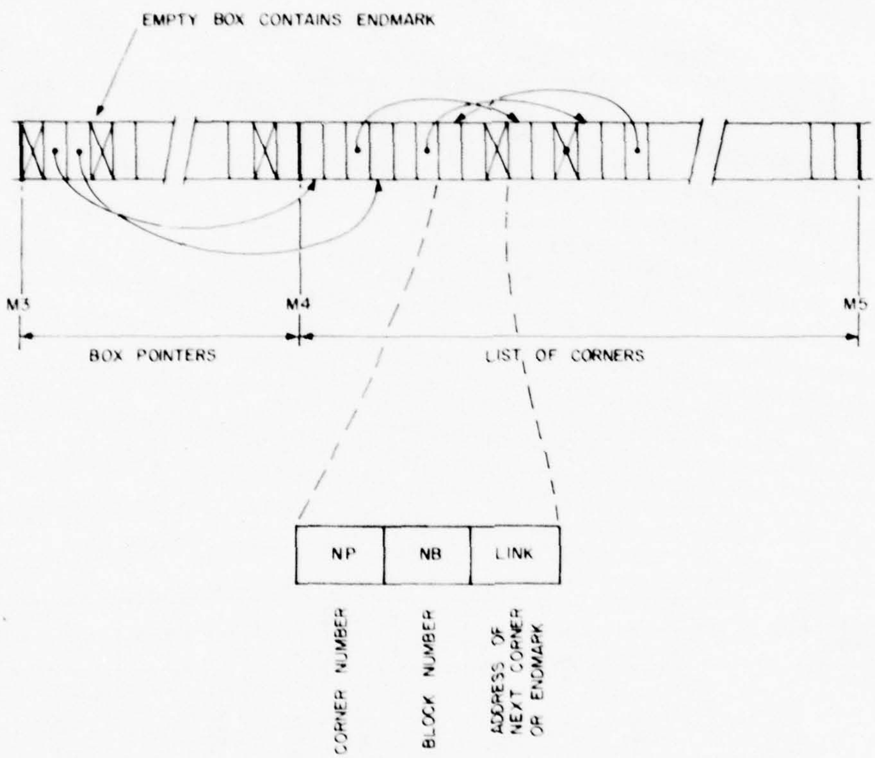


FIGURE 2.3 LINKED LIST OF BLOCK CORNERS BY BOX

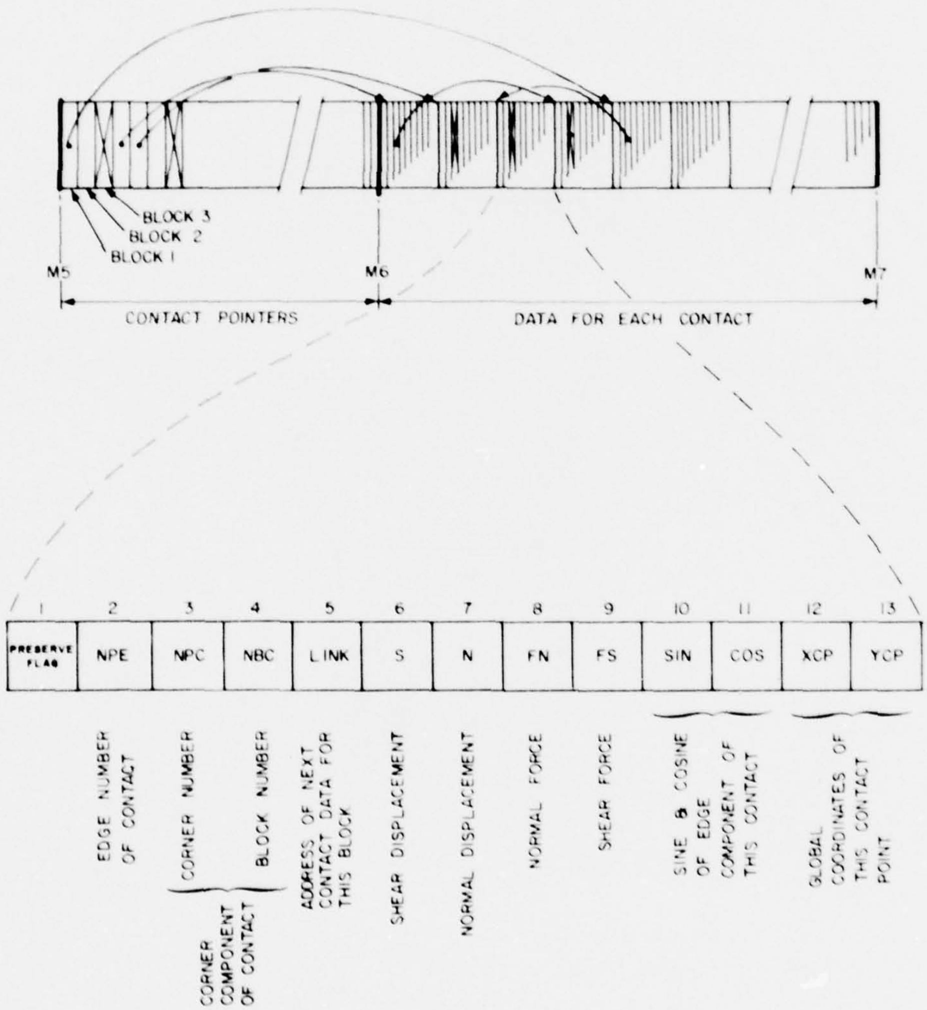


FIGURE 2.4 CONTACT DATA LISTS

The program indicates values of 0.459 and 0.114 respectively.

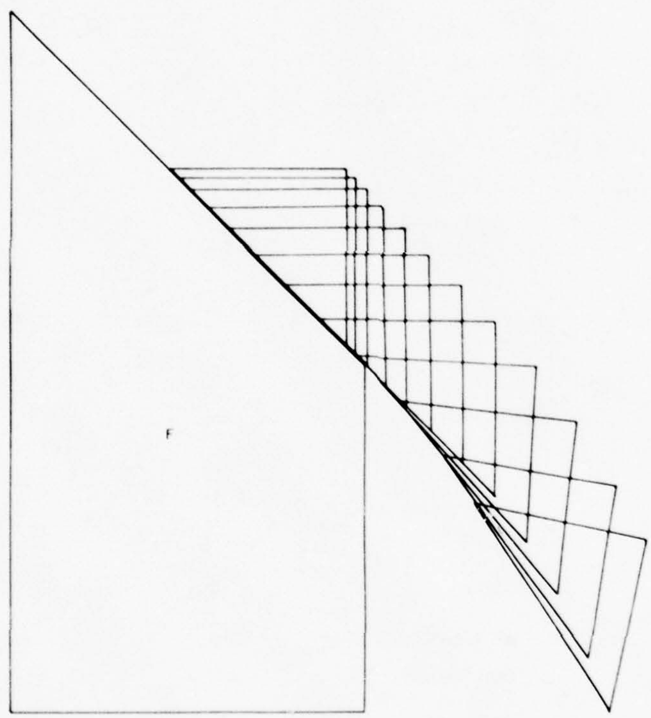


FIG. 2.5 VALIDATION 1 - BLOCK SLIDING AND TOPPLING

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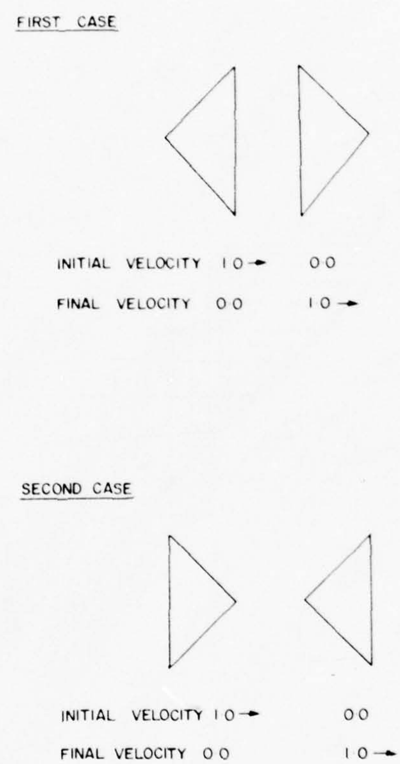
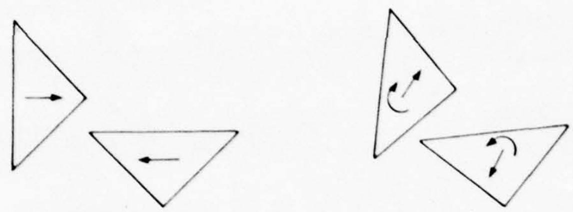
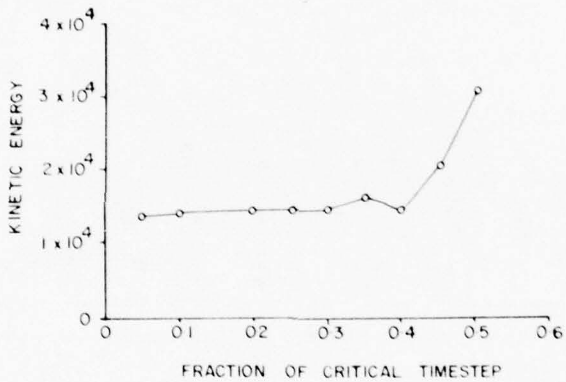


FIG. 2.6 VALIDATION 2 - IMPACT OF TWO BLOCKS





FRACTION OF CRITICAL TIMESTEP	TOTAL KINETIC ENERGY $\times 10^4$	TOTAL MOMENTUM $\times 10^5$
0·50	3·13	9·645
0·45	2·11	9·645
0·40	1·47	9·645
0·35	1·62	9·645
0·30	1·52	9·645
0·25	1·49	9·645
0·20	1·44	9·645
0·10	1·40	9·645
0·05	1·39	9·645
BEFORE IMPACT	1·39	9·645

FIG. 2.7 VALIDATION 3 - EFFECT OF TIMESTEP ON ENERGY AND MOMENTUM CONSERVATION

DAMES & MOORE

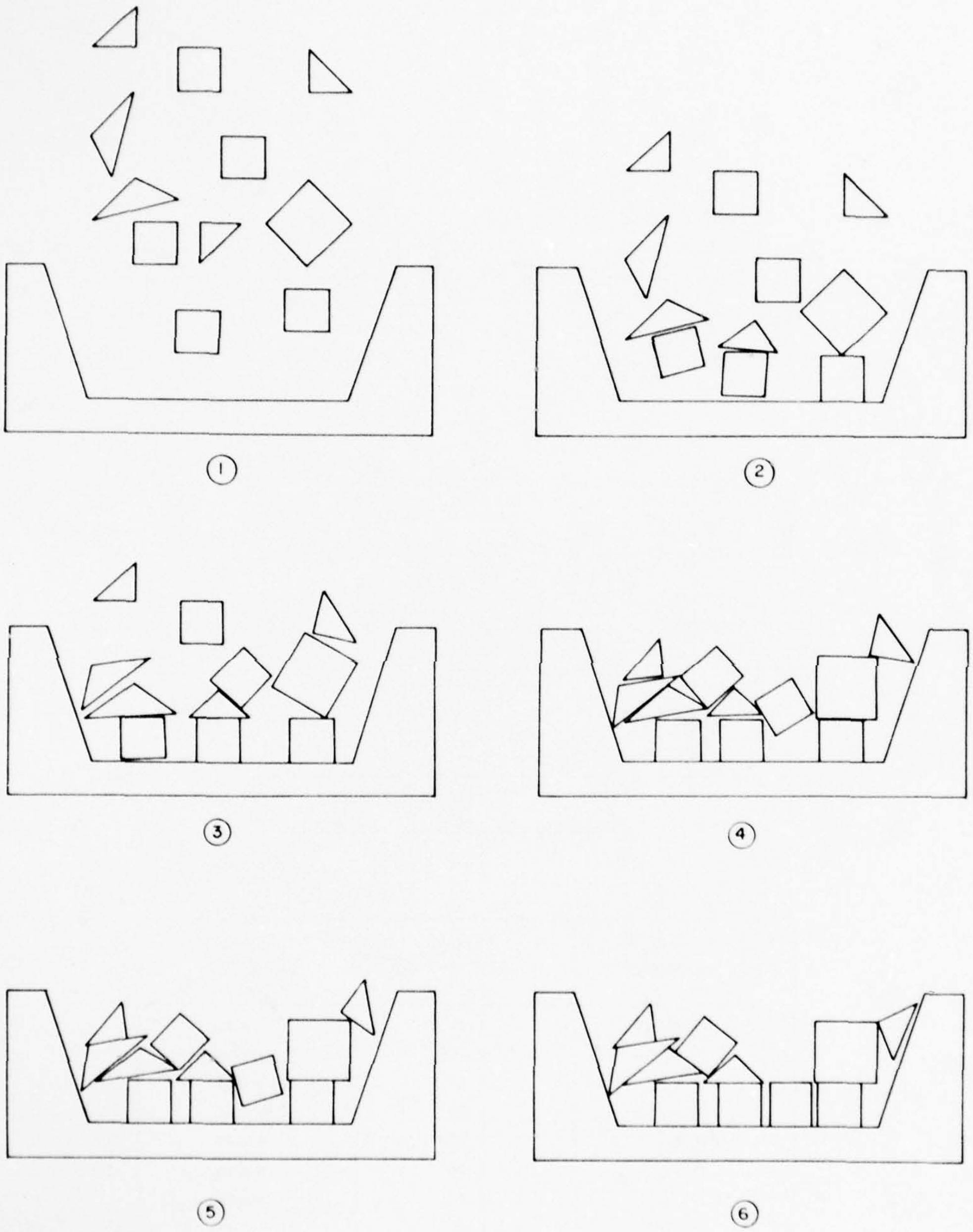
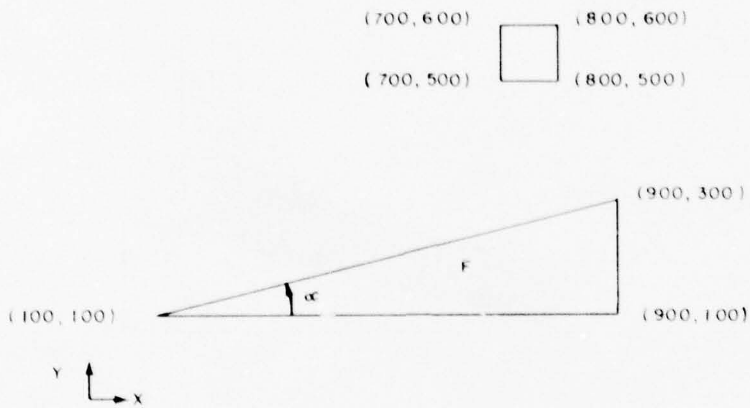


FIG. 2.8 VALIDATION 4 - BLOCKS FALLING INTO A RECEPTACLE

DAMES & MOORE



INPUT DATA

μ	= 0.30	FRICTION
α	= ARCTAN (0.25)	ANGLE OF PLANE
g_y	= −9.81	GRAVITY
ρ	= 1.00	DENSITY
$k_n = k_s$	= 10^7	SHEAR AND NORMAL STIFFNESS

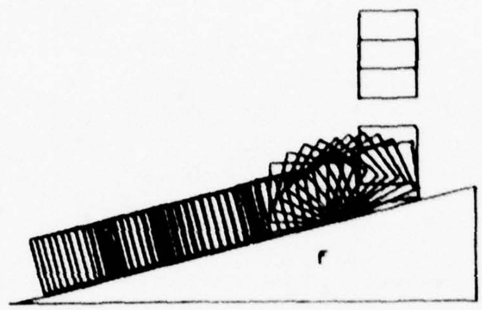
FRACTION = 0.1

$\left.\begin{array}{l} \lambda = 0.5 \\ f = 5.0 \end{array}\right\}$ RAYLEIGH DAMPING PARAMETERS

CALCULATED TIME STEP $\Delta T = 6.3246 \times 10^{-3}$

FIG. 2.9 VALIDATION 5 – INITIAL GEOMETRY

2.10 (a)



2.10 (b)

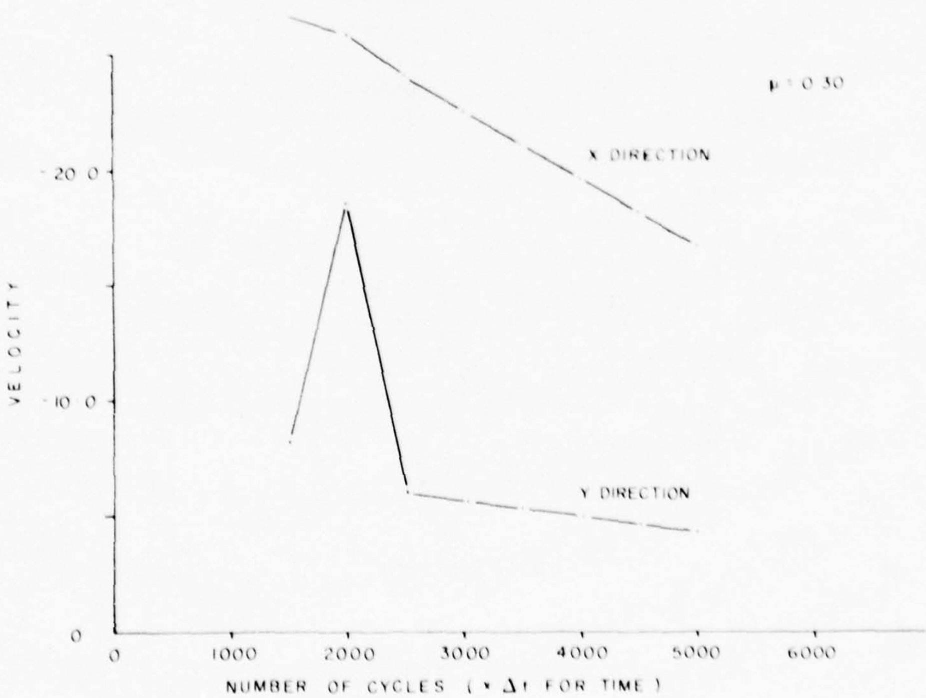


FIG. 2.10 VALIDATION 5 - CASE A

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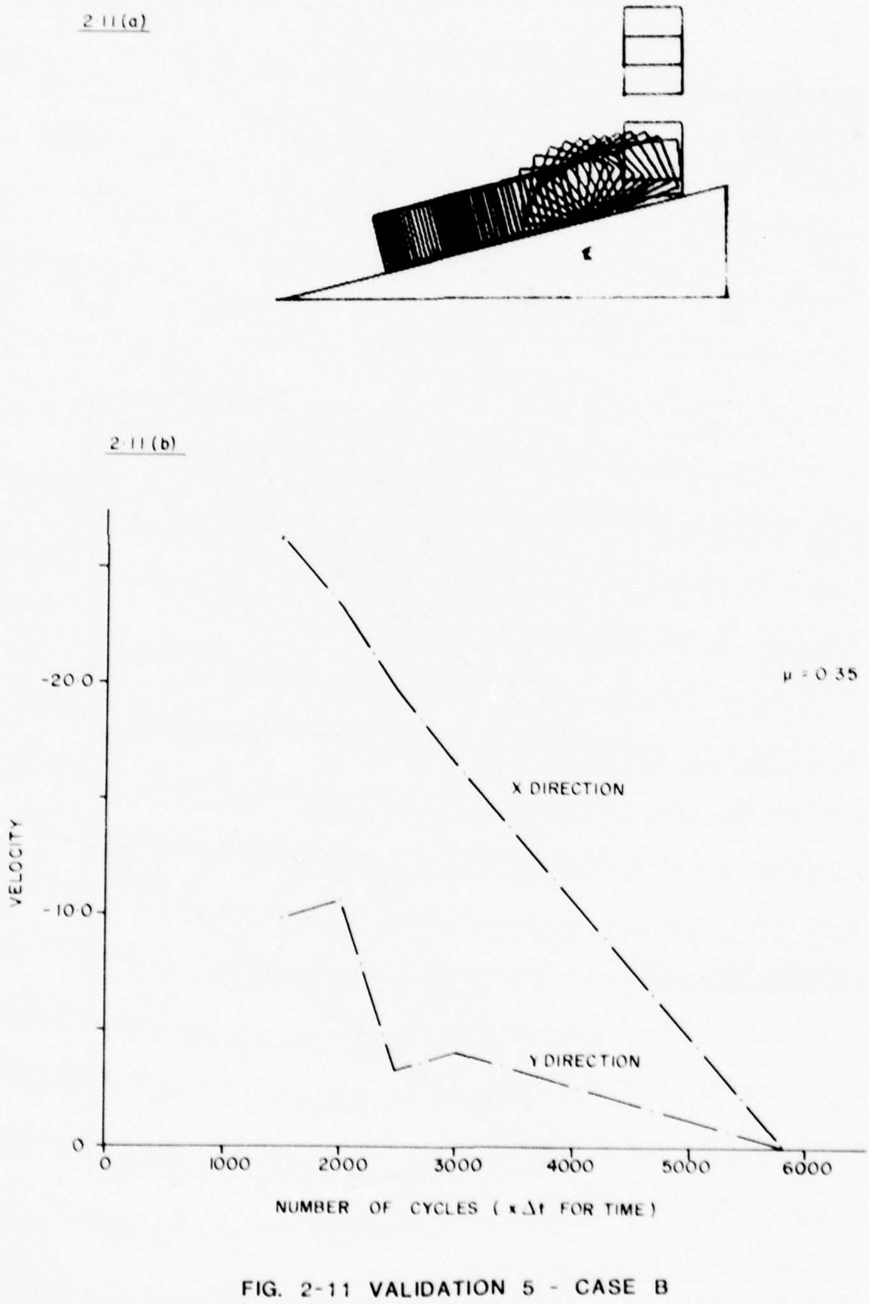

FIG. 2-11 VALIDATION 5 - CASE B

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a) SLOPE CONFIGURATION FROM GOODMAN AND BRAY'S PAPER (1976)

b) INITIAL PLOT FROM PROGRAM RBM

c) "SNAPSHOT" PLOT FROM RBM SHOWING FAILURE MODE FOR A FRICTION COEFFICIENT OF 0.65

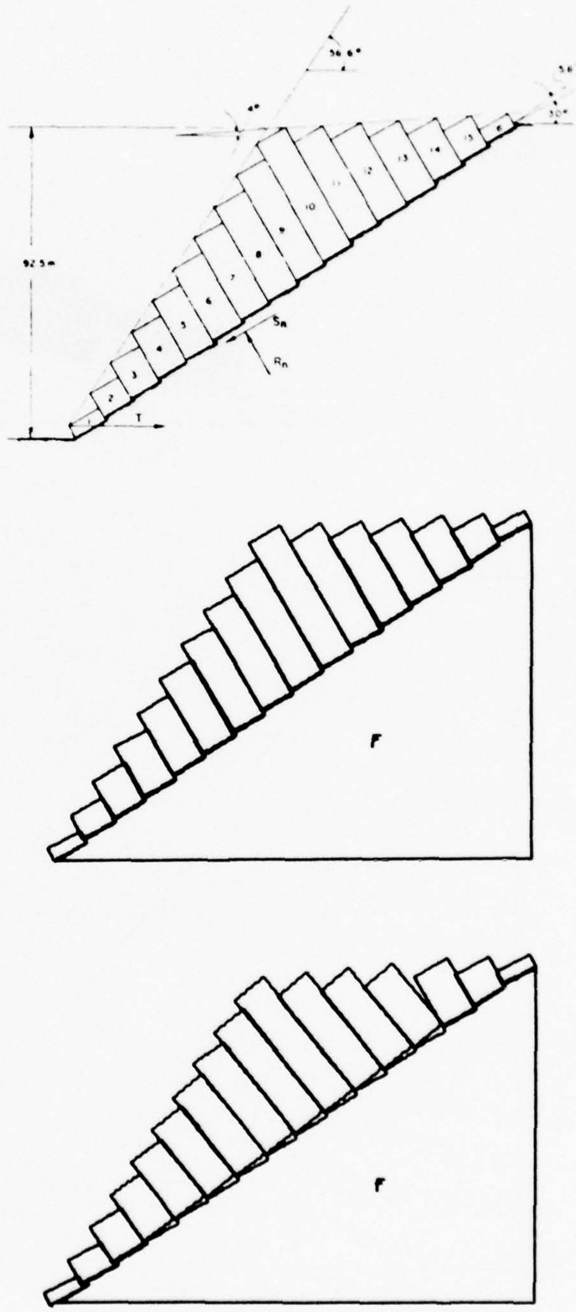


FIG. 2.12 VALIDATION 6 - TOPPLING FAILURE OF A ROCK SLOPE

DAMES & MOORE

CHAPTER 3: SIMPLY-DEFORMABLE PROGRAM, SDEM

3.0 *This Chapter describes the introduction of limited deformability into the blocks of the distinct element method, as a simpler alternative to the general approach of Chapter 6. Examples and validations are given.*

3.1 INTRODUCTION

The scheme described in this section is an extension of the distinct element method (DEM) in which limited deformability is given to each element. It is an attempt to preserve the simplicity and efficiency of the DEM while extending its usefulness in modelling high stress applications. The new program, SDEM, is intended for representing rock systems where the intact behaviour of the rock, although affecting significantly the mechanics of the system, does not participate strongly enough for the more complex deformation modes to contribute much to the overall deformation.

However, for situations involving blocks of rock with complex shapes, or with complex loading, and which also undergo large deformations of the intact material, there is no alternative but to discretize the block itself in order to provide the many degrees of freedom that can permit the block to deform in an adequately complex manner. This approach is taken with program DBLOCK, which is described in Section 6.

The simplifications embodied in SDEM are concerned only with the number of degrees of freedom associated with block deformations; the constitutive laws can be completely general, and include plasticity and arbitrary non-linearity. It should be appreciated that the approach described in this section has not yet been fully explored, and that evolution will take place as experience is accumulated: the formulation that has been presented should not be taken in any sense as the optimum.

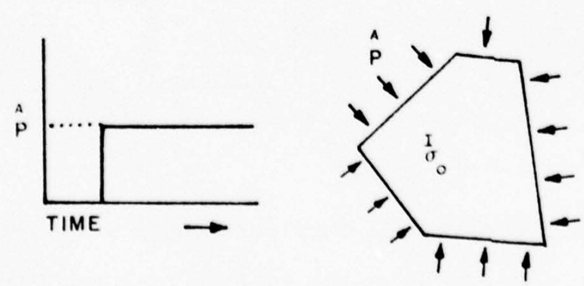
A listing of SDEM is given in Appendix XI. The input commands are almost identical to those of RBM, except for some changes noted in Section 3.5

3.2 SIMPLIFIED EXPLANATION OF DEFORMABLE-BLOCK APPROACH

In order to give the reader a physical picture of what is involved in the new formulation, a descriptive account of the behaviour of a block deforming volumetrically is presented below. The general formulation is given later.

3.2.1 VOLUMETRIC DEFORMATION

Consider an arbitrary block suddenly exposed to a uniform pressure, $\overset{A}{p}$:

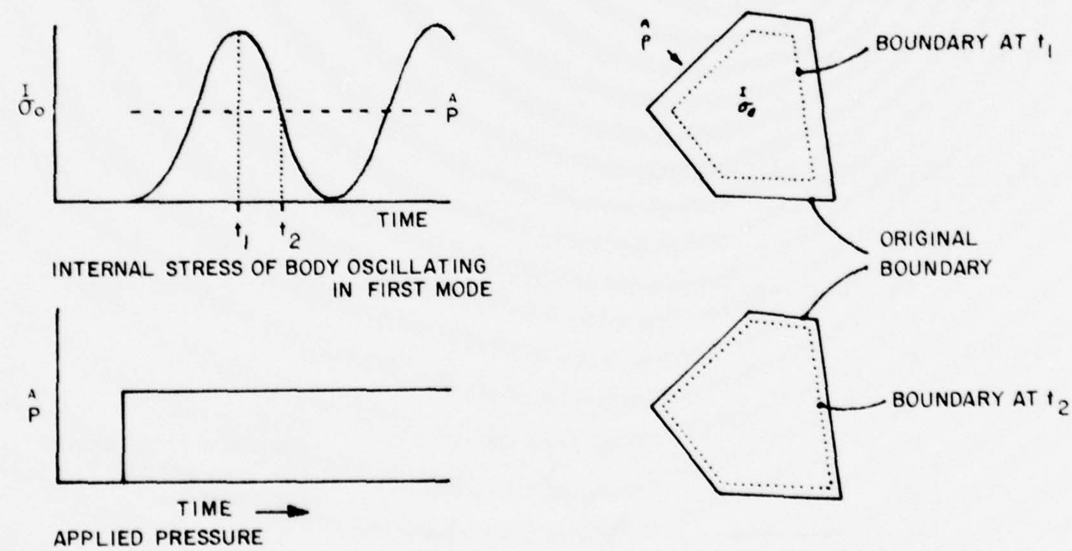


NOTE:
SUPERSCRIPT "A" STANDS FOR "APPLIED" AND "I" FOR "INTERNAL"

Instantaneously, nothing will happen owing to the finite wave speed in the solid. In particular, the isotropic stress in the interior of the solid, $\overset{I}{\sigma}_o$, will be zero at the instant that the pressure is applied, and will build up gradually as the pressure wave reaches the interior of

th block. In addition, the boundaries of the block will move inwards towards the centre due to the volumetric compression of the material.

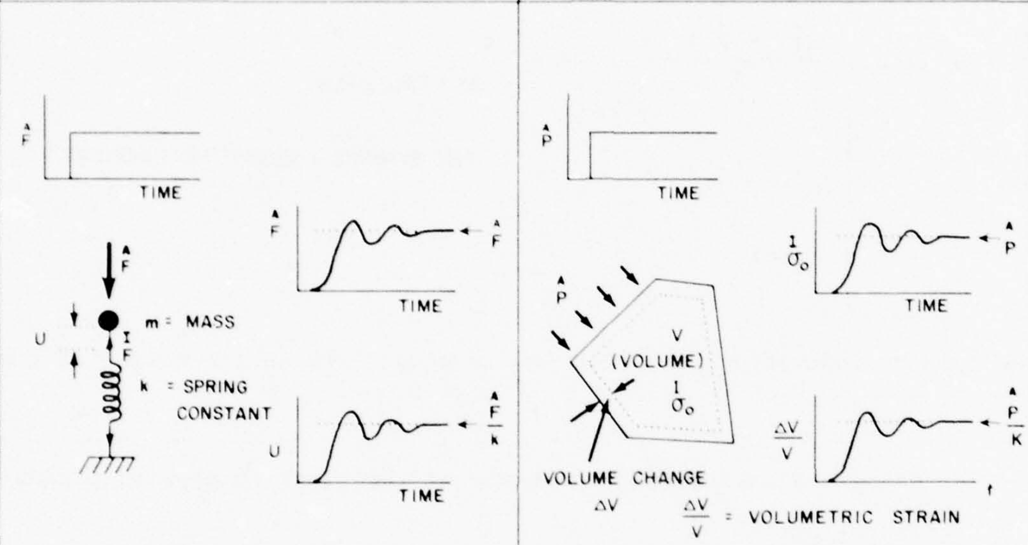
Over a larger time span the internal stress and the boundary displacements will be oscillatory, and will consist of a summation of the many natural modes of oscillation of the body. The predominant mode, however, will be the fundamental, which corresponds to all points in the body moving either inwards or outwards in phase:



The internal isotropic stress will oscillate about a mean value equal to the applied pressure, and will converge to this pressure after internal damping has dissipated all dynamic energy.

The behaviour described above - that of a solid body oscillating in its first volumetric mode - is simply that of a single degree-of-freedom oscillator, such a mass-spring system, being excited by a step force. The analogy between the block and the mass-spring system is as follows:

MASS-SPRING SYSTEM	BLOCK WITH APPLIED PRESSURE



$\hat{F}$ APPLIED FORCE	$\hat{P}$ APPLIED PRESSURE
$\overset{I}{F}$ SPRING FORCE	$\overset{I}{\sigma_o}$ INTERNAL ISOTROPIC STRESS
U DISPLACEMENT	$\frac{\Delta V}{V} = \epsilon_v$ VOLUMETRIC STRAIN
$\dot{U}$ VELOCITY	$\dot{\epsilon}_v$ VOLUMETRIC STRAIN-RATE
m MASS	m^e EFFECTIVE MASS
k SPRING CONSTANT	K BULK MODULUS
$U^{EQUIL} = \frac{\hat{F}}{K}$ EQUILIBRIUM DISPLACEMENT	$\epsilon_V^{EQUIL} = \frac{\hat{P}}{K}$ EQUILIBRIUM VOLUMETRIC STRAIN
$\omega_o = \sqrt{\frac{k}{m}}$ NATURAL ANGULAR FREQUENCY	$\omega_o = \sqrt{\frac{K}{m^e}}$ NATURAL ANGULAR FREQUENCY

NOTE: HERE, m^e IS THE "MASS" NECESSARY FOR THE NATURAL FREQUENCY ω_o TO BE EQUAL TO THAT OF THE FIRST VOLUMETRIC MODE. ITS EVALUATION WILL BE TREATED IN APPENDIX V.

The central-difference algorithm for computing the response of the mass-spring system is as follows:

$$\dot{u} := \dot{u} + \frac{(\overset{A}{F} - \overset{I}{F})\,\Delta t}{m}$$

$$\overset{I}{F} := \overset{I}{F} + k\dot{u}\,\Delta t$$

Δt = TIME STEP

THE SYMBOL := MEANS "REPLACED BY"

Here, F is an independent variable and is prescribed as a function of time.

Using our analogy, the response of the block to applied pressure takes the same form:

$$\dot{\epsilon}_v := \dot{\epsilon}_v + \frac{(\overset{A}{P} - \overset{I}{\sigma}_0)\,\Delta t}{m^e}$$

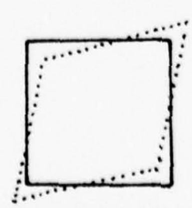
(LAW OF MOTION FOR BLOCK STRAIN)

$$\overset{I}{\sigma}_0 := \overset{I}{\sigma}_0 + K\,\dot{\epsilon}_v\,\Delta t$$

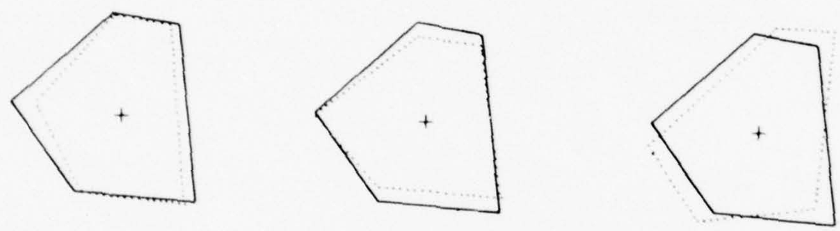
(CONSTITUTIVE LAW FOR BLOCK)

3.2.2 Other Modes of Deformation

Analogies similar to that described above can be made for other simple modes of deformation, such as a shear mode:



In general, any number of independent modes of deformation (oscillation) may be taken. However, in the program three modes are used, corresponding to the three strains in two dimensions i.e. ε_{11}, ε_{22}, $\varepsilon_{12} + \varepsilon_{21}$.* These modes are visualised as follows:



ε_{11} $\qquad$ ε_{22} $\qquad$ $\varepsilon_{12} + \varepsilon_{21}$

In addition to these modes there remain of course the three rigid-body modes considered by the original block program (two translational and one rotational degrees of freedom), making six degrees of freedom per block in total.

3.2.3 Coupling of Blocks

The degrees of freedom described above are associated with each block individually. Blocks are coupled together via the joint stiffnesses, whose formulation is unchanged from that of the original rigid block program. However, there now are two additional stages in the calculation:

*In this section, ε_{ij} is taken as the partial derivative of the i displacement with the j co-ordinate.

3.2.3.1 Applied Stress Derived from Boundary Forces

The average stress in a closed volume can be derived from the forces acting on the boundary of the volume, using Gauss' divergence theorem. In this way the "applied stress" on the block is evaluated from the set of forces developed by the contacts around the block. Thus:

$$\hat{\sigma}_{ij} = \frac{\sum^{c} \overset{c}{F}_i \, \overset{c}{X}_j}{V}$$

in tensor notation, where

$\sum^{c}$ represents the sum over all contacts, and

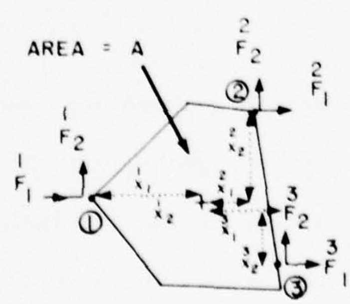
V is the block volume (= area in 2 dimensions)

$\overset{c}{F}_i$ are the forces at contact **c**

$\overset{c}{X}_j$ are the co-ordinates of contact **c** relative to the centroid

For example, the applied pressure $\hat{p}$ used in 3.2.1 is given by:

$$\hat{p} = \frac{1}{2}\left(\hat{\sigma}_{11} + \hat{\sigma}_{22}\right) = \frac{\sum^{c} \overset{c}{F}_1 \overset{c}{x}_1 + \sum^{c} \overset{c}{F}_2 \overset{c}{x}_2}{2A}$$

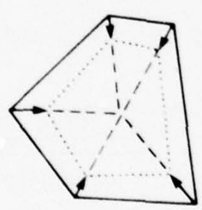


$$\hat{p} = \frac{\overset{1}{F}_1 \overset{1}{x}_1 + \overset{2}{F}_1 \overset{2}{x}_1 + \overset{3}{F}_1 \overset{3}{x}_1 + \overset{1}{F}_2 \overset{1}{x}_2 + \overset{2}{F}_2 \overset{2}{x}_2 + \overset{3}{F}_2 \overset{3}{x}_2}{2A}$$

3.2.3.2 Boundary Displacements Derived from Strains

In the original block program, the displacement increments at block boundaries were evaluated in order to give normal and shear increments of displacement at contacts, which would then allow contact forces to be found. The boundary displacements were derived from the known centroid displacements and rotation.

For deformable blocks, the displacements at a block boundary are also functions of the strains in the block. For example, in the case of a volumetric compression, at each boundary point the displacement vector is directed inwards towards the centroid, with a magnitude proportional to the distance from the centroid:



BOUNDARY DISPLACEMENTS DUE TO VOLUMETRIC COMPRESSION

In general, for strain increments referred to orthogonal axes, the expression for boundary displacement increments is:

$$\Delta u_i^c = (\Delta\epsilon_{ij} + \Delta R_{ij})\, x_j^c + \Delta u_i$$

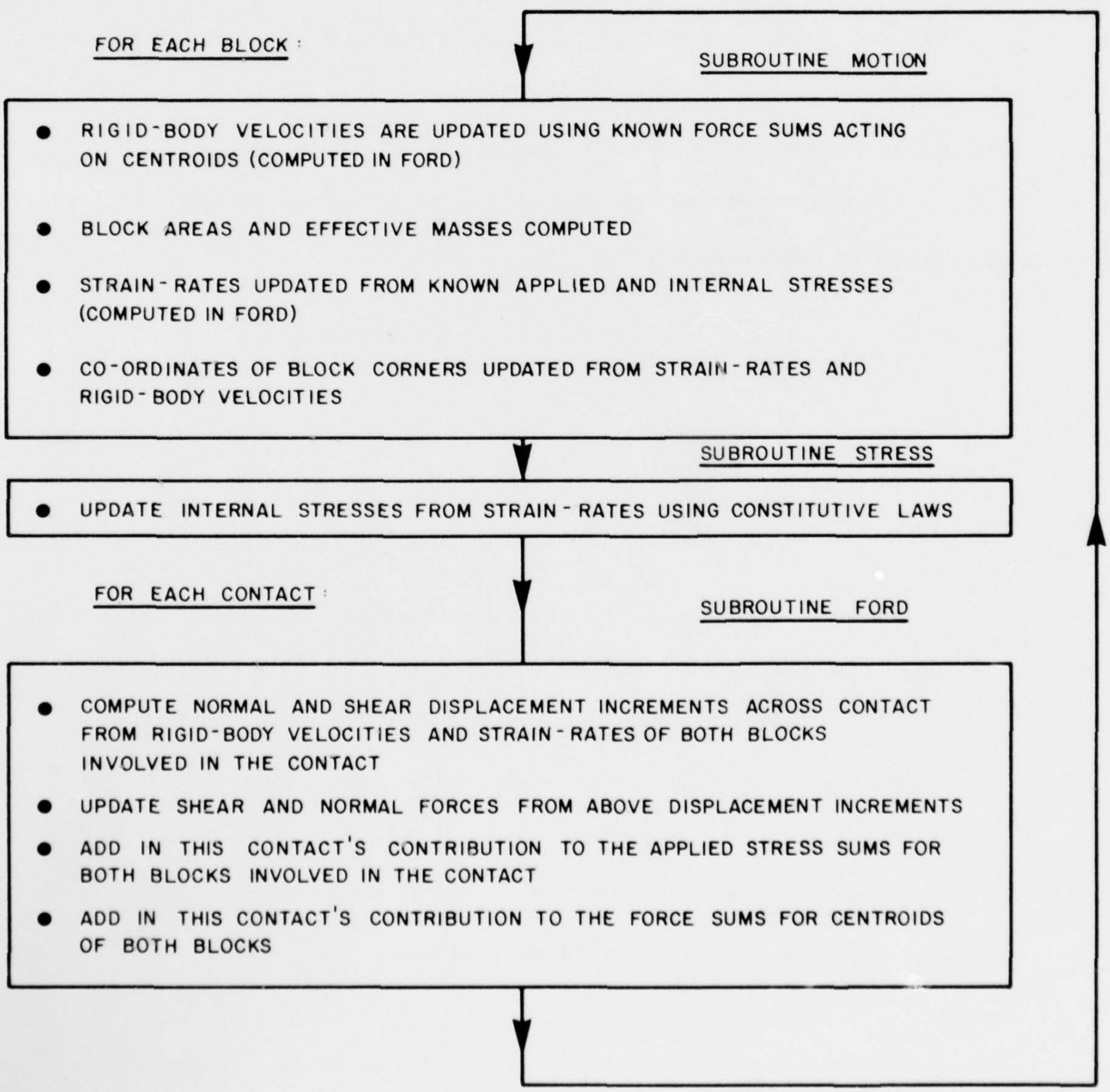
Here, the superscript "c" stands for "contact" or "corner".

The terms ΔR_{ij} and Δu_i are the rotation and rigid-body translations that were used in the rigid-block program.

x_j^c are the co-ordinates of contact c relative to the centroid.

3.3 SEQUENCE OF OPERATIONS

Before giving the mathematical treatment of the calculation method, it may be useful to present a flow diagram in order to get an overall picture of what happens in the program:



3.4 MATHEMATICAL TREATMENT

The equations corresponding to the flow diagram given in Section 3.3 are presented below. Tensor notation is used for subscripts i,j, and k only, where repeated indices imply summation over the index.

Indices:	i, j, k	These have values 1,2 and refer to orthogonal coordinates.
	c	Contact or corner number.
	R	means "relative"
	P, E	These superscripts are intended to distinguish between the two blocks participating in a contact. "P" refers to the block contributing the corner, and "E" refers to the block contributing the edge to the edge/corner contact.
Symbols:	x_i	Centroid coordinates of block.
	$\dot{x}_i$	Centroid velocities of block.
	ΔX_i	Incremental shear and normal displacements at a contact.
	P_i	Shear and normal forces at a contact.
	Q_i	Global contact forces.
	$\dot{\theta}$	Angular velocity of block (anticlockwise positive).
	$\dot{R}_{ij}$	Skew-symmetric tensor equal to $\begin{bmatrix} 0 & \dot{\theta} \\ -\dot{\theta} & 0 \end{bmatrix}$
	ℓ_i	Maximum block widths.
	$\dot{\varepsilon}_{ij}$	Strain rate for a block.
	$\overset{A}{\sigma}_{ij}$	Applied stress on a block.
	$\overset{C}{x}_i$	Global coordinates of contact point or block corner.
	$\overset{I}{\sigma}_{ij}$	Internal stress in a block

$\dot{x}_i^c$ Velocities of contact point or block corner.

F_i Force sums on block centroid.

M Moment sum on block centroid.

a $= 1 - \frac{\alpha \Delta t}{2}$

b $= 1/(1 + \frac{\alpha \Delta t}{2})$

c $= \beta/\Delta t$, where α, β are the Rayleigh damping parameters.

$\left.\begin{matrix} a^e \\ b^e \end{matrix}\right\}$ Same as a and b, but with α defined for internal block damping.

g_i Acceleration due to gravity.

I Moment of inertia for block.

m Block mass.

A Block area.

$m^e_{(i)}$ Effective block mass for strain-rate calculations (see Appendix V).

K Bulk modulus for block material.

G Shear modulus for block material.

μ Friction coefficient for contacts.

k_{ij} Contact stiffnesses, equal to $\begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix}$

where k_s = shear stiffness;

k_n = normal stiffness.

δ_{ij} Kronecker delta = $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

e_{ij} A tensor

$= \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$

:= means "replaced by"

(i) Subscripts in parentheses indicate non-tensorial character.

The following calculations are done for all blocks (subroutines MOTION & STRESS):

Rigid-body velocities:

$$\dot{x}_i := (a\dot{x}_i + (\frac{F_i}{m} + g_i)\Delta t)b$$

$$\dot{\theta} := (a\dot{\theta} + \frac{M}{I}\Delta t)b$$

$$F_i = 0$$

$$M = 0$$

Block areas and effective masses:

$$A = \tfrac{1}{2}\sum_{c=1}^{c=n-1}\left\{(\overset{c}{x}_1 + \overset{c+1}{x}_1)(\overset{c+1}{x}_2 - \overset{c}{x}_2)\right\} + \tfrac{1}{2}(\overset{n}{x}_1 + \overset{1}{x}_1)(\overset{1}{x}_2 - \overset{n}{x}_2)$$

(n = number of corners for the block)

$$\ell_i = \max_{c=1,n}(\overset{c}{x}_i) - \min_{c=1,n}(\overset{c}{x}_i)$$

$$m^e_{(i)} = \frac{m(\ell_i)^2}{4A}$$

Strain-rates:

$$\dot{\varepsilon}_{ij} := (a^e\dot{\varepsilon}_{ij} + \frac{\overset{A}{\sigma}_{ij} - \overset{I}{\sigma}_{ij}}{m^e_{(j)}}\Delta t)b^e$$

$$\overset{A}{\sigma}_{ij} = 0$$

Corner displacements:

$$\dot{\overset{c}{x}}_i = \dot{x}_i + (\dot{\varepsilon}_{ij} + \dot{R}_{ij})(\overset{c}{x}_j - x_j)$$

$$\overset{c}{x}_i := \overset{c}{x}_i + \dot{\overset{c}{x}}_i\Delta t$$

Rigid-body displacements:

$$x_i := x_i + \dot{x}_i\Delta t$$

Internal stresses:

$$\overset{I}{\sigma}_{ij} := \overset{I}{\sigma}_{ij} + ((K-\tfrac{2}{3}G)\dot{\varepsilon}_{kk}\delta_{ij} + 2G\dot{\varepsilon}_{ij} + \dot{r}_{ij})\Delta t,$$

where $\dot{r}_{ij}$ are the stress rotation correction terms derived in Appendix VI, and are given by:

$$\dot{r}_{ij} = \Delta\sigma_{ij}/\Delta t = -(\sigma_{kj}\dot{R}_{ik} + \sigma_{ik}\dot{R}_{jk})$$

The following calculations are done for all contacts (subroutine FORD):

Velocities of corner relative to edge at a contact:

$$\dot{x}_i^R = \dot{x}_i^P - \dot{x}_i^E + (\dot{\varepsilon}_{ij}^P + \dot{R}_{ij}^P)(\overset{C}{x}_j - x_j^P) - (\dot{\varepsilon}_{ij}^E + \dot{R}_{ij}^E)(\overset{C}{x}_j - x_j^E)$$

Incremental shear and normal displacements:

$$\Delta X_i = J_{ij}\dot{x}_j^R \Delta t \ ,$$

where $J_{ij} = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix}$

and γ = angle between x_1 and X_1 axes.

Shear and normal forces:

$$\Delta P_i = k_{ij}\Delta X_j$$

$$P_i := P_i + \Delta P_i$$

$$D_i = c\Delta P_i$$

$$\begin{array}{lll}
\text{If } P_2 > 0 & \longrightarrow & \left.\begin{array}{l} P_i = 0 \\ D_i = 0 \end{array}\right\} \\
\text{Otherwise} & & \\
\downarrow & & \\
\text{If } |P_1| > \mu|P_2| & \longrightarrow & P_1 = \mu P_2 \ \mathrm{sign}\ (P_1) \\
\text{Otherwise} & & D_i = 0
\end{array}$$

Global contact forces:

$$Q_i = H_{ij}\ (P_j + D_j) \qquad , \text{ where } H_{ij}J_{jk} = \delta_{ik}$$

Contributions to centroid force sums:

$$F_i^P := F_i^P - Q_i$$

$$M^P := M^P - Q_j\ (\overset{C}{x}_i - x_i^P)e_{ij}$$

$$F_i^E := F_i^E + Q_i$$

$$M^E := M^E + Q_j\ (\overset{C}{x}_i - x_i^E)e_{ij}$$

Contributions to applied stresses in blocks:

$$\hat{\sigma}_{ij}^P := \hat{\sigma}_{ij}^P - Q_i\ (\overset{C}{x}_j - x_j^P)\ /A^P$$

$$\hat{\sigma}_{ij}^E := \hat{\sigma}_{ij}^E + Q_i\ (\overset{C}{x}_j - x_j^E)\ /A^E$$

Notes: 1) The computer program departs slightly from the formulation given above, in that:

a) the normal force, P_2, is stored with the opposite sign convention from that implied above - i.e. it is taken as positive in compression;

b) the applied stresses are stored in the block data arrays as $A\sigma_{ij}$, not σ_{ij}. The division by A is done once only in MOTION, and not for each contribution in FORD, as indicated above.

2) At present, two shear stresses (σ_{12} and σ_{21}) and two shear strain-rates ($\dot{\varepsilon}_{12}$ and ε_{21}) are calculated, as well as the moment and rotation for a block. In other words the program is operating as if there were seven degrees of freedom per block, whereas there are only six. Although this redundancy apparently causes no problems, it is unnecessary and should be removed in future versions.

3.5 CHANGES TO PROGRAM RBM

The following changes were made to the baseline program RBM (described in Section 2.0) in order to introduce simple deformability into the blocks:

1. The structure of the data lists for blocks was changed, but the system of pointers shown in Figure 2.1 was retained. The new data list is given in Figure 3.1. A new variable, NVARB, was introduced to facilitate future changes to the block data list. NVARB equals the number of words in the block data list, excluding the corner and length data. It is currently set at 24. Changes were made to all routines that contained references to the length of the block data list.

2. The corner co-ordinates stored in the block data lists were altered from local co-ordinates to global co-ordinates. Hence the corner co-ordinates of each block must be updated at each cycle. As a result, functions GLX and GLY were eliminated. Subroutines NEXT, MOTION, REBOX, UPDAT and BPLOT were modified to reflect the change from local to global co-ordinates.

3. Subroutine REBOX was modified to enable it to operate on individual corners rather than on whole blocks. This was

made possible because the global co-ordinates of each corner are known at each cycle, so that re-boxing can be triggered as each corner crosses an integer boundary. The calling sequence for REBOX was moved from CYCLE to MOTION to reflect the different philosophy.

4. Subroutines FORD and MOTION were changed to incorporate the deformable-block calculations described in Section 3.4. New listings of the complete program are given in Appendix XIII.

5. A new subroutine STRESS was added. This routine updates *internal stresses* from strain rates. The constitutive law is utilized in this routine, but at present elasticity only is used.

6. Several changes were made in NEXT to enable parameters pertaining to block deformability to be specified. The following commands were added:

ELASTIC	K,G	Defines bulk modulus, K and shear modulus, G for rock.
BDAMPING	DAMP, FREQ	Defines internal damping parameters for blocks.
LOCK ON / OFF		LOCK ON forces joints to remain in contact once they have touched; i.e., infinite tensile strength is implied. However, sliding can still occur. LOCK OFF returns the behaviour to normal. This is the default setting.

The commands CHECK and LOAD are withdrawn temporarily. Other commands are identical to those of RBM (see Appendix III).

7. A free-format input routine, PARSE, was incorporated in the program. This enables command parameters to be entered in any columns, separated by blanks or commas. The command word can be any length greater than or equal to four characters. Subroutine NEXT was modified to call PARSE.

3.6 EXAMPLES AND VALIDATIONS

3.6.1 EXAMPLE

Figure 3.2 shows that the static deformations of a block resting on the edge of a table, with different values of various parameters. The block was elastic with small elastic moduli, in order to demonstrate the capability of the program to treat large deformations.

3.6.2 RIGID-BLOCK COMPARISON

Comparison runs were made of a block falling on a plane, both with the program RBM (original program with rigid blocks) and with the new program SDEM with very high elastic moduli. The results were almost identical, which is to be expected, since the formulations become identical

when the strain-rates tend to zero. Figure 3.3 shows the block falling on the plane for the two cases of high modulus and low modulus. It is interesting to note that the block slows down more in the low modulus case, presumably because more energy goes into internal vibration, which is then dissipated by the internal damping.

3.6.3 CONTINUUM VALIDATION

In the limit of very high joint stiffness an assemblage of blocks should resemble a *continuum*, both statically and dynamically. The column of blocks shown in Figure 3.4 was used to check this aspect.

In all runs, the "LOCK ON" option was used, in which all contacts, once created, were locked in the normal direction, but with slip possible in the shear direction when permitted by the value of friction. Three cases were treated: unconfined column and confined column in compression, and column in shear. The column was loaded by applying gravity either in the x or y directions. For the dynamic cases, the mass damping and internal damping were zero, with the joint stiffness-proportional damping as follows:

fraction of critical = 0.1

frequency = 10.0

For the static cases, the stiffness-proportional term was set to zero, and the mass damping was as follows:

$$\text{Mass damping} \begin{cases} \text{fraction of critical} = 1.0 \\ \text{frequency} = 0.03 \end{cases}$$

$$\text{Internal damping} \begin{cases} \text{fraction of critical} = 0.5 \\ \text{frequency} = 0.25 \end{cases}$$

The case of confined compression was modelled by setting a high value of joint friction, which prevents lateral deformation of the blocks. For unconfined compression zero friction was used. Other properties were as follows:

Joint stiffnesses: $k_n = 2.0 \times 10^7$

$k_s = 2.0 \times 10^7$

Material properties:

Bulk modulus: $K = 2.0 \times 10^4$ } for
Shear modulus: $G = 0.428572 \times 10^4$ } compression tests
(Poisson's ratio = 0.4)

Bulk modulus: $K = 1.0 \times 10^4$ } for
Shear modulus: $G = 1.0 \times 10^4$ } shear test

Density: $\rho = 1.0$

Applied gravity: $g_y = -1.0$, for compression tests
$g_x = 0.1$, for shear test

Column height: $L = 800$

Column width: $W = 100$

Number of blocks: $n = 8$

The moduli appropriate to the various modes of deformation were as follows:

confined compression	unconfined compression	shear
$K + \frac{4}{3} G$	$\dfrac{4G(\frac{1}{3}G + K)}{(K + \frac{4}{3} G)}$ (plane strain Young's modulus)	G
2.5714×10^4	1.4286×10^4	1.0×10^4

In the results that follow, the theoretical values for natural period of oscillation and static deflection were calculated as follows:

Natural period, $T = 4L\sqrt{\dfrac{\rho}{E^*}}$

Static displacement of top block centroid $\quad \delta = \dfrac{-g\rho\,(L^2 - x^2)}{2E^*}$

where E^* is the appropriate modulus selected from the above table

x is the distance from the top of the column to the top block centroid (50 units, in this case)

RESULTS

		mode		
		confined compression	unconfined compression	shear
DYNAMIC	theoretical	20.0	26.77	32.0
Period, T	measured	19.8	24.4	32.1
STATIC	theoretical	12.4	22.3	
displacement δ	measured	12.4	21.0	not performed

Notes: (1) The period T was taken over only one or two cycles of oscillation, and was thus subject to some error.

(2) The ratio of σ_{11} to σ_{22} in the confined static case was also measured, and conformed well with the theoretical value.

3.6.4 PLASTIC FLOW DEMONSTRATION

A run was made to illustrate the unique capabilities of program SDEM to model slip on the discontinuities of a complex joint pattern simultaneously with large-strain plastic flow in the intact material. This type of simulation would probably be quite difficult to do with existing finite element or finite difference programs. SDEM handles it quickly and efficiently.

For the purpose of the run, a simple Von Mises yield law and associated flow rule was inserted into subroutine STRESS. The formulation was similar to that presented by Wilkins (1969).

Figure 3.5, frame 1, shows the initial geometry of the rock blocks. The triangular blocks were 100 units on the side with density of 1.0 unit. The "missile" was much heavier, with a density of 10 units, and was given a y-velocity of -40 units. Joint stiffnesses were 10^7 units and bulk and shear moduli 10^7 units also. The yield stress was set at 10^2 units, and joint friction coefficient 0.2. Frames 2 to 10 show "snapshots" of the

system every 100 cycles after impact. It should be noted that the two block corners of initial impact were initially set very slightly apart, in order to allow entry for the missile.

From the sequence of frames, large plastic strains can be observed in some of the blocks, together with gross joint displacements. Although it may not be obvious from the pictures, the missile is being simultaneously deflected to the right, and slowed down.

Although only a simple plasticity law was used in the example, more complex formulations with non-associated flow rules can be inserted into the program, literally in a matter of minutes. Such formulations are currently being used extensively in continuum finite difference programs such as DAMSEL (Cundall, 1976).

For interest, Figure 3.6 shows an identical run as Figure 3.5, but performed with the rigid block program RBM. All physical constants are the same (except of course the intact elastic and plastic properties) and the frames are plotted at the same time intervals. It can be seen that the missile is slowed down almost instantaneously to a very low velocity. The momentum is transferred to the blocks, particularly the lower row, which is propelled downwards at high speed. The simulation was stopped after Frame 7, since one of the lower blocks had reached the limit of the computation field (box area), as evidenced by the "fix" flag that has been attached to it. It should be noted that line 51 of routine UPDAT (see Appendix XII)

was removed for the purposes of this run. This statement deletes the contact if the normal displacement exceeds 3 units, which is the case for the present simulation, where the transient forces are very high.

3.6.5 COMPARISON OF PROGRAM SPEEDS

It is difficult to compare the speed of the new program SDEM with the old, rigid-block program RBM, since the run times depend on how many contacts exist, how large the blocks are compared to the box area, and how many updates are done during the run. As a rough check, both programs were run on the Goodman and Bray validation problem described in Section 2.5, using 300 time steps. During this time RBM did 13 updates and SDEM did 21, due to the higher deformability and the different update logic. The ratio of executing times (excluding problem setup and printout) was 1 to 1.6.

3.7 CONCLUSIONS AND RECOMMENDATIONS

A means has been devised to give the blocks of the distinct element method the freedom to deform in simple ways. Although the tests performed on the new program have been quite limited so far, the results look promising. The formulation allows large displacements within blocks, so that large plastic flows of intact material could be modelled together with slip on complex joint sets. No change has been made to the scheme of edge-to-corner contacts for representing joints between blocks although the scheme described in Chapter 5 could be used. The new program SDEM was found to be slower than RBM by a ratio of 1.6 to 1.

The new program, SDEM, can be regarded as filling the gap between the original distinct element method and the general lagrangian scheme (with re-zoning of sliding contacts) that has been studied in Chapter 6.0. There are definite limitations to program SDEM that the general program will not have. For example, there seems to be no obvious way to make SDEM represent a true continuum without joints. It is true that, in the limit of very stiff joints between blocks, the behaviour tends to that of a continuum, but this is achieved only at the expense of considerable computer time, since the time step is forced to be very small due to the joints. Furthermore, the approximation to a continuum is only good for triangular blocks; in this case the formulation is similar to that of constant strain finite elements or finite difference zones. As the number of edges increases beyond three, the blocks look "stiffer" because they still only have three degrees of freedom to deform even though their large number of edges implies that they should have a correspondingly large number of degrees of freedom.

A useful future development could be to arrange for blocks to have the same number of degrees of freedom as the number of edges. In other words, a greater number of stress and strain terms would be stored for a block with many edges than for a block with few edges. The additional stress and strain terms could be derived from the differentials of stress and strain with respect to the spacial co-ordinates. Although this proposed formulation would treat quasi-static problems more realistically, it is not clear whether it would be good for problems where wave propagation was important.

This section presents only the initial attempt at representing block deformability. No doubt as the topic is explored further, better ideas will appear.

3.8 ACKNOWLEDGEMENT

The motivation for developing the new method came from the meeting of September 20, 1977 at DNA, where Ivan Sandler, Russell Duff and others expressed their concern that the simplicity and efficiency of the distinct element program would be lost with the general deformable block program, and that perhaps a middle line could be taken in which simple deformability would be added to the original procedure.

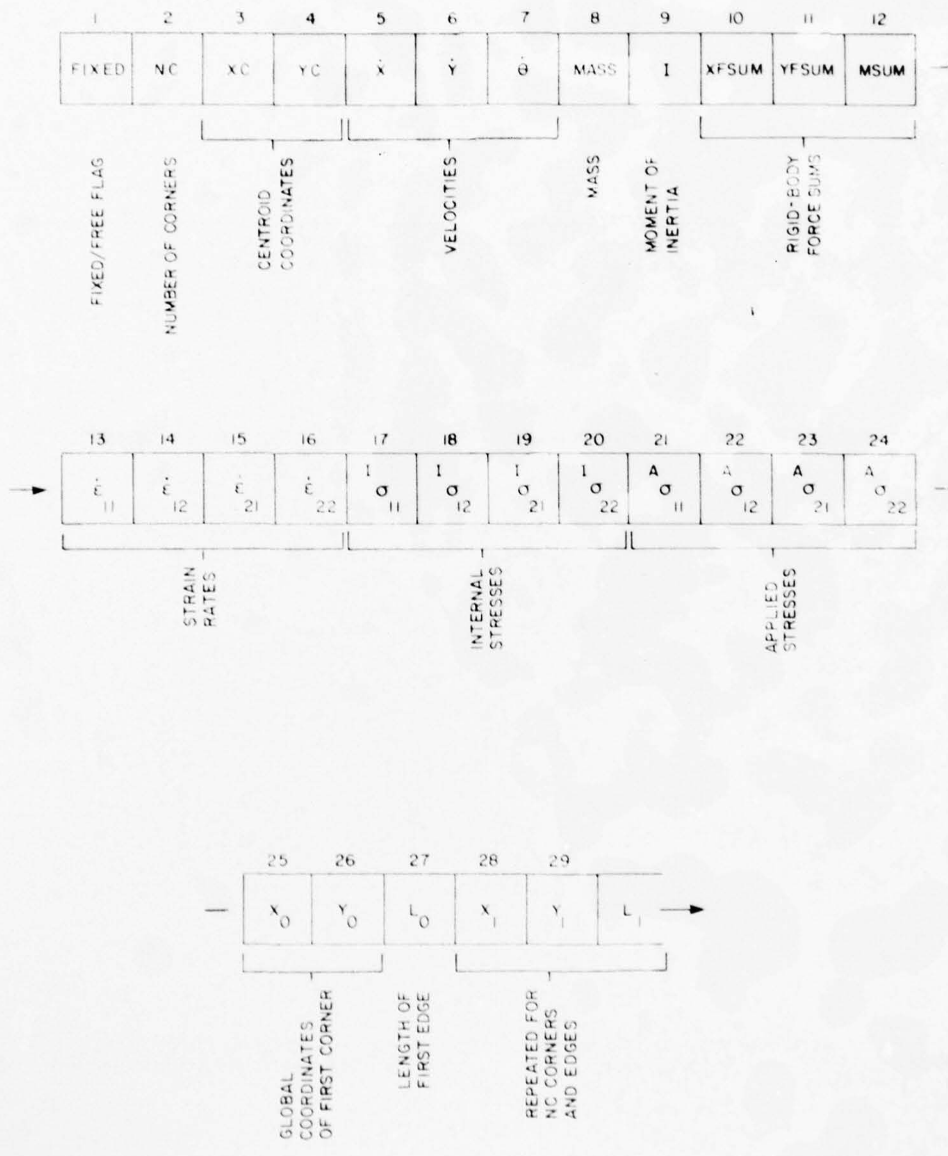
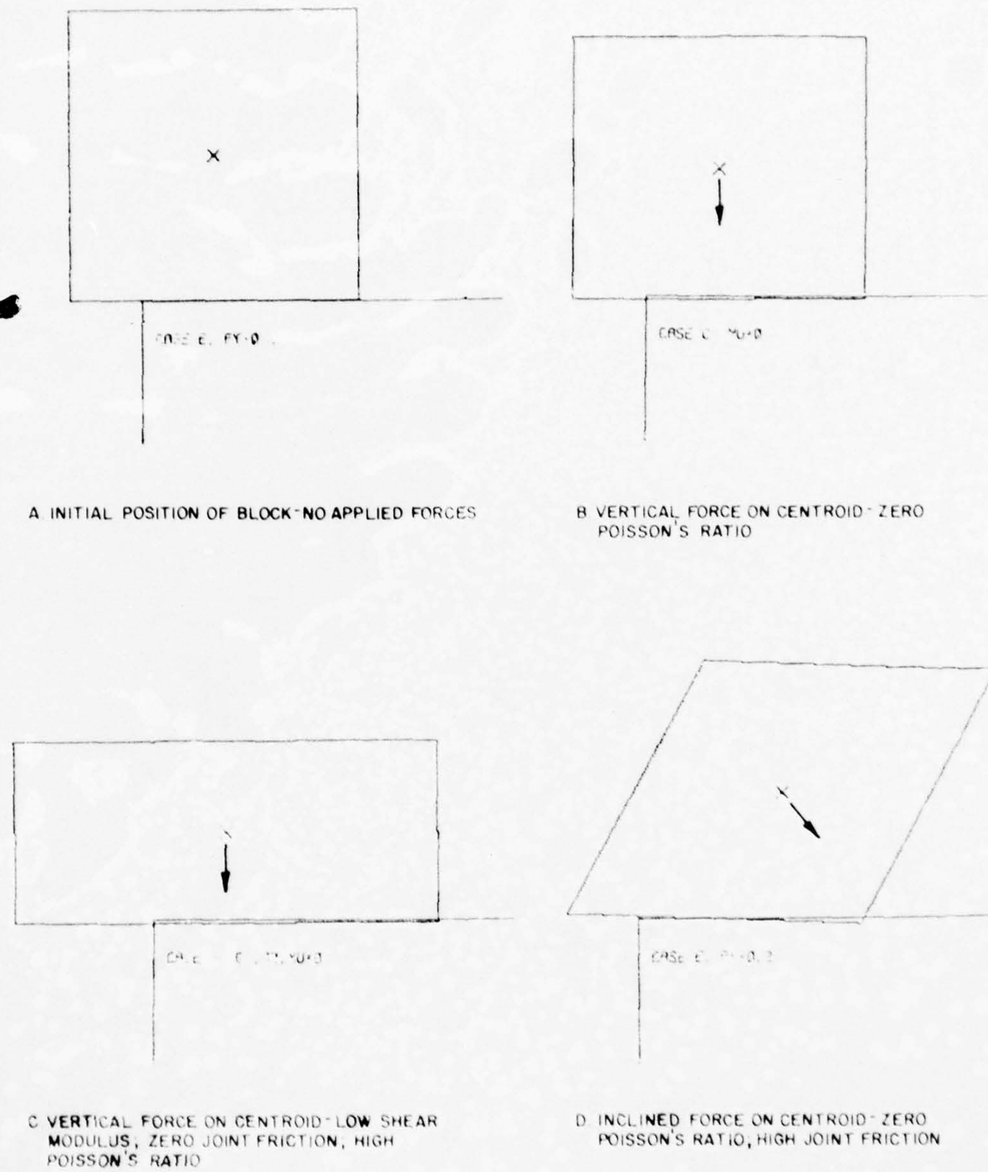


FIG. 3.1 DATA ARRAY FOR BLOCKS - PROGRAM SDEM



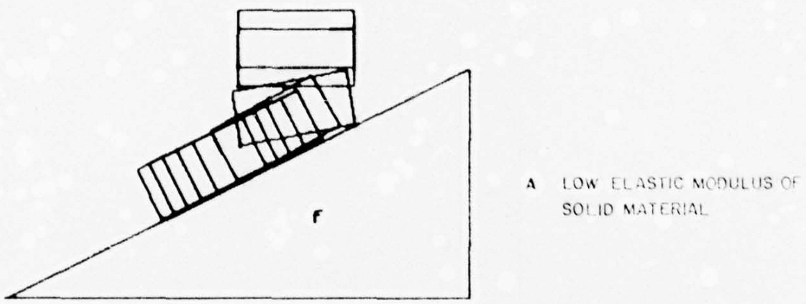
A INITIAL POSITION OF BLOCK-NO APPLIED FORCES

B VERTICAL FORCE ON CENTROID-ZERO POISSON'S RATIO

C VERTICAL FORCE ON CENTROID-LOW SHEAR MODULUS, ZERO JOINT FRICTION, HIGH POISSON'S RATIO

D INCLINED FORCE ON CENTROID-ZERO POISSON'S RATIO, HIGH JOINT FRICTION

FIG. 3.2 STATIC DEFORMATION OF A SINGLE BLOCK ON A RIGID TABLE. THE PLOTS SHOW THE STATIC EQUILIBRIUM POSITIONS OF THE BLOCK UNDER VARIOUS LOADS AND MATERIAL PROPERTIES. ALL DEFORMATIONS ARE REAL, AND NOT MAGNIFIED



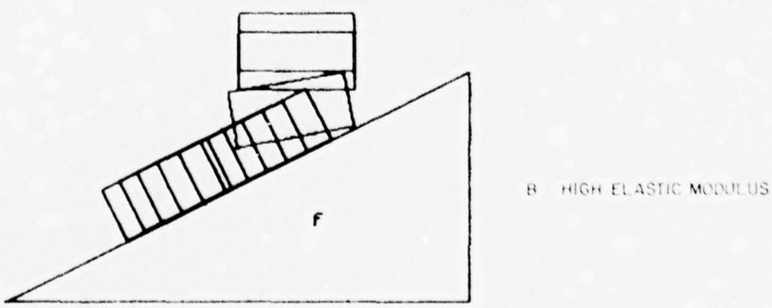


FIG. 3.3 BLOCK FALLING ON TO PLANE - FRICTION ANGLE IS SLIGHTLY HIGHER THAN BLOCK ANGLE

DAMES & MOORE

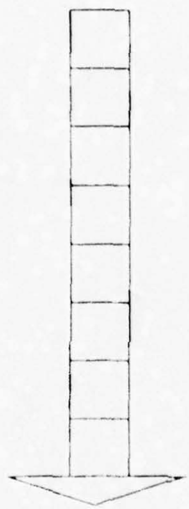


FIG. 3.4 CONFIGURATION OF BLOCKS USED FOR CONTINUUM VALIDATION

DAMES & MOORE

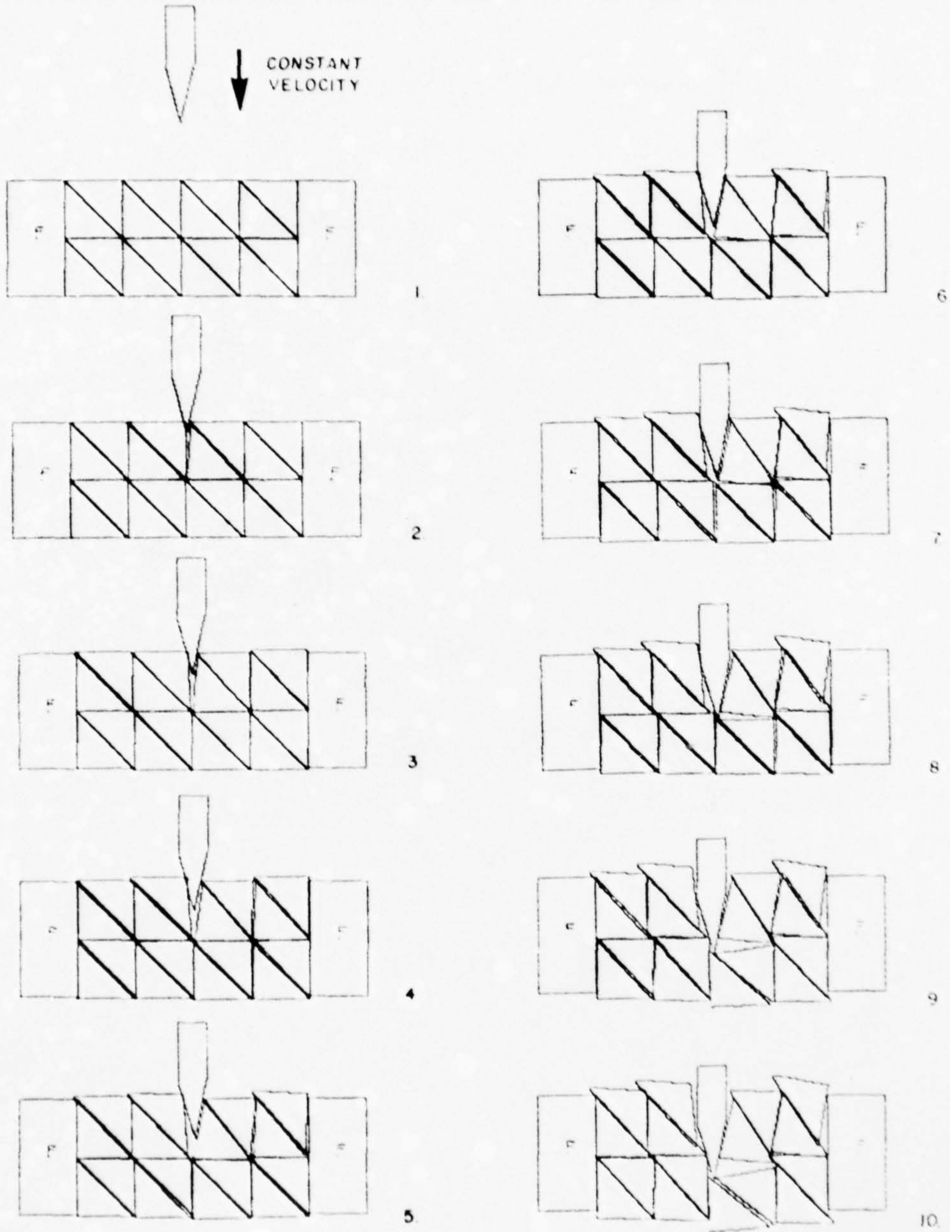


FIG. 3.5 PENETRATION TEST WITH PLASTIC FLOW AND JOINT SLIP - PROGRAM SDEM

DAMES & MOORE

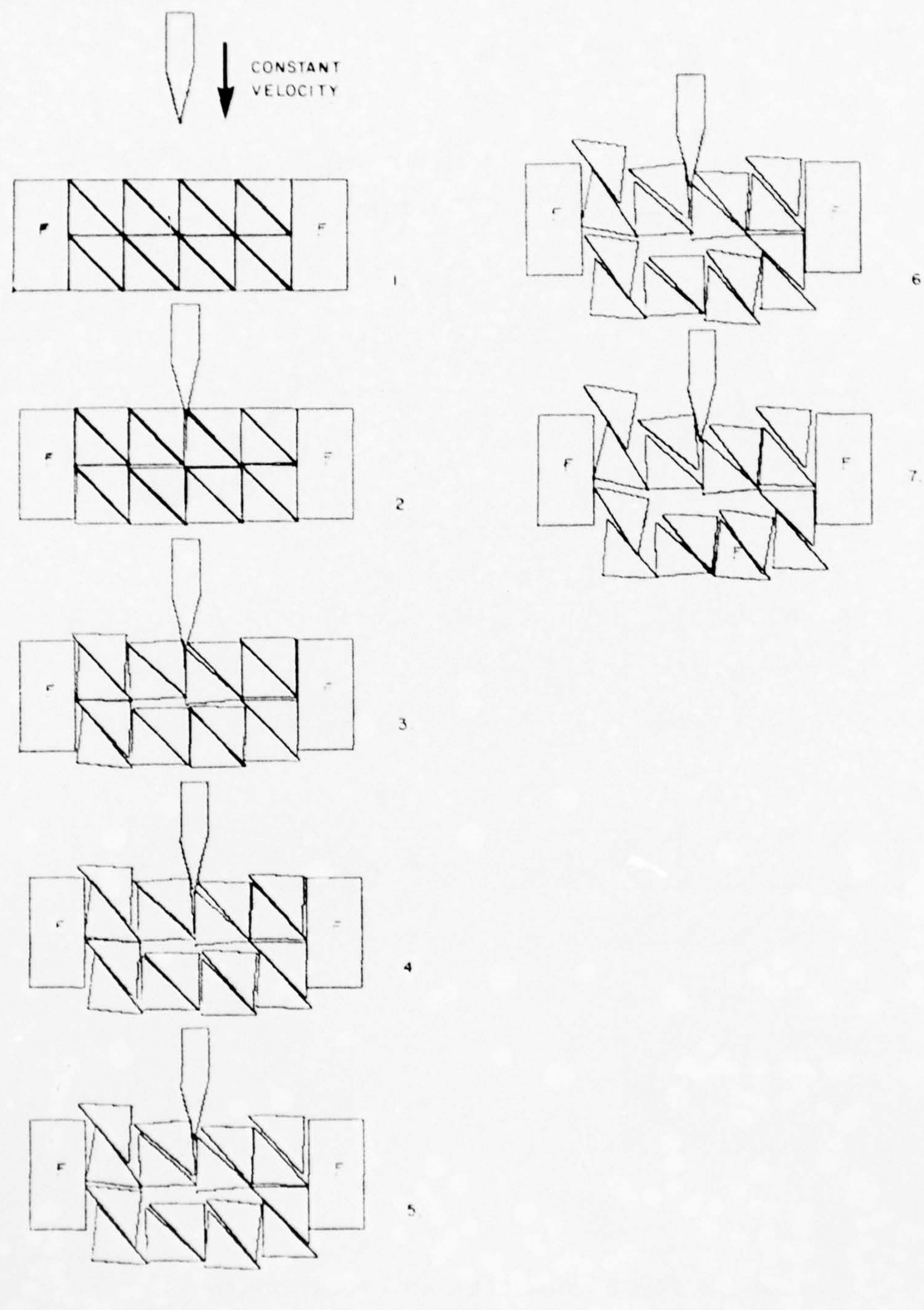


FIG. 3.6 AS FOR FIG. 3.5, BUT USING RIGID BLOCKS - PROGRAM RBM

CHAPTER 4: INTRODUCTION OF CRACKING INTO THE RIGID-BLOCK PROGRAM

4.0 *A new version of RBM is described with modified data structures that allow blocks to be subdivided repeatedly in an efficient manner according to simple crack criteria. Several simple examples are given.*

4.1 INTRODUCTION

It is often observed that cracking of intact blocks occurs during laboratory tests on jointed models. Presumably the same sort of thing happens in the field.

Two commonly-observed behaviour-patterns are: cracking of corners and cracking across a block in a manner similar to that of the Brazilian test. It would seem that the realism of the rigid-block program would be considerably enhanced if simple cracking modes could be allowed. For the two modes mentioned, even raw empirical data could be used as the criteria for cracking, although a number of algebraic relations have been proposed to represent the results from tests such as the point-load test (Franklin & Broch). The point here is that it is probably not necessary to go to sophisticated laws, requiring much computer time, in order to increase the realism of the rigid block program considerably. On the contrary, if cracks are not permitted, the modelling of many problems is rendered seriously unrealistic, since "locking-up" occurs when only small overlaps exist between block corners. In practice these corners would break off at relatively low loads, and allow the block motion to continue. Even a crude cracking law is better than no cracking law. In any event, once cracking is permitted, parameter studies may be made, so that the effect of crack criterion on overall behaviour can be determined.

The program RBM was modified to allow blocks to split under the action of applied loads, using user-defined criteria. The new program was

written in such a way that alternative crack criteria can be inserted easily into a skeleton subroutine provided for the purpose. In this subroutine the user is given a list of loads that are currently being applied to each block, together with their location. It is up to the user to determine whether a crack will form, and, if so, where it will form. The built-in logic then splits the block into two, and carries out the various housekeeping tasks, such re-numbering, re-boxing, etc.

4.2 CHANGES TO DATA STRUCTURES

It was necessary to make several changes to the data structures in order to render the program efficient when applying the crack criterion and during the creation of new blocks. The major changes in program logic were as follows:

- Both edges and corners are mapped into boxes (not just corners, as in RBM). This is to ensure that a newly-created block will be guaranteed of finding all possible nearby blocks by interrogating the boxes that it maps into.

- Each contact is pointed to by both blocks concerned (rather than from just one block as in RBM). The reason for this is that any crack criterion needs, for a given block, to have available to it all the contacts involving that block.

- Block corners are stored in a circular linked-list, pointed to by the data for the block concerned. The linked-list format was necessary because corners would have to be re-allocated to new blocks, as blocks cracked. Edge lengths are not stored now.

- Updating (i.e. searching for, and creating new contacts) is now done locally, for each corner that crosses an integer boundary. This was made possible by storing the global coordinates for corners, rather than local. Local updating should be more efficient for most problems.

The detailed changes will now be examined.

4.2.1 FIXED AREAS OF MEMORY

The new program, RBMC, now has only two fixed areas in memory (see Figure 4.1): the lower area contains one word for each potential block. These words point to the data array for each block, which can now be anywhere in the linked-list area. The other fixed area contains one word per box, with each word being a pointer to a list of blocks that map into that box.

4.2.2 BLOCK DATA STRUCTURE

Each block is allocated a basic array of contiguous data as well as a variable-length linked-list containing the corner-coordinates. This arrangement is shown in Figure 4.2, which also gives the format for the two data structures. At the start of a new run the user must estimate the total number of blocks that are likely to be needed during the run. The area of memory between M1 and M2 is allocated on the basis of this estimate. Although the maximum number of blocks must be specified in advance, any number of corners can be accommodated, within the limits of the main memory area.

4.2.3 BOX ENTRIES

Each box (which corresponds to one word between M2 and M3) contains either zero, indicating that no blocks map into it, or a pointer

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COMPUTER MODELING OF JOINTED ROCK MASSES.(U)

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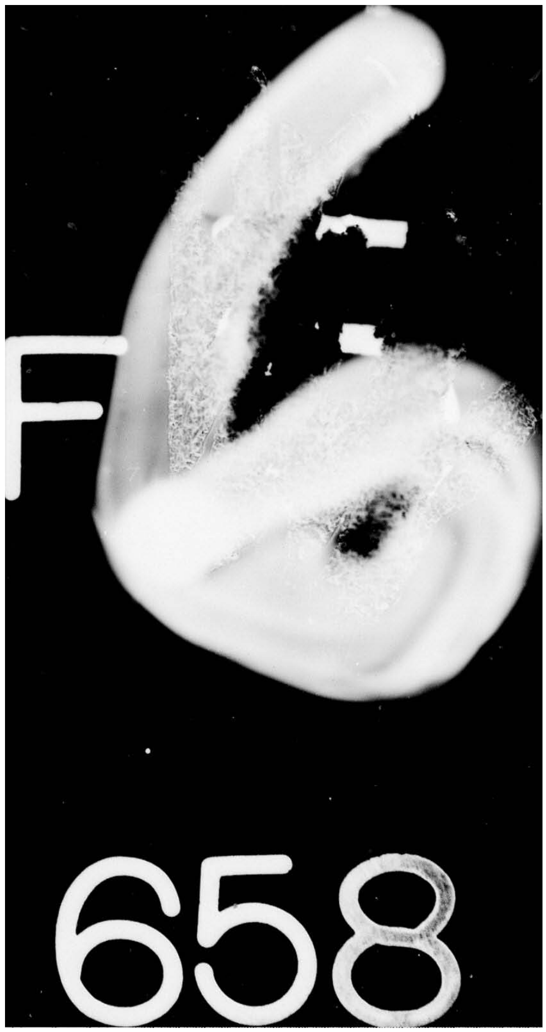
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to a linked-list of double words. The list gives the block numbers of all blocks that map into that box. In contrast to RBM, corner numbers are not stored, since both corners and edges cause entries to be deposited into the boxes that they cross. Figure 4.3 shows the scheme of box entries.

4.2.4 CONTACT DATA

As mentioned previously, each contact is pointed to by both blocks comprising that contact. Word 14 of the block data array (see Figure 4.2) points to a linked-list of double-words that serve as pointers to all the contacts for that block. Figure 4.4 shows such a list pointing to several contacts. Each of the contacts is also pointed to by similar lists emanating from the other blocks involved in the contacts. Figure 4.4 also gives the format of a typical contact array. It will be noted that word 4 contains the block number of the block contributing the corner to the edge/corner contact. It is necessary to store this number to ensure that during scanning for contacts, the forces due to each contact will only be taken once. This is done as follows: if all blocks are scanned, and the corresponding contact lists interrogated, each contact will be accessed twice. However, if the identification number of accessing block is equal to the contents of word 4 of the contact data, the contact is skipped for the purposes of updating that contact. On the other hand, when the accessing block number is not equal to the contents of word 4, the contact is processed, and the resulting forces added into the force sums for the two blocks concerned (which is possible because now both block numbers are known).

4.2.5 EMPTY LISTS

There are four types of data structures located in the linked-list area from M3 to M4:

1) Basic block data arrays, with 14 words;
2) Linked list of corners, consisting of triples;
3) Contact data arrays, of 12 words;
4) Linked lists of doubles, serving either as box entries or contact pointers.

Only two empty lists are maintained, corresponding to 3 and 4 above, since both the number of blocks and the number of corners (1 and 2 above) will always increase, so that there will never be redundant memory associated with these entities. However, numbers of contacts and doubles will fluctuate. Redundant contact arrays are linked together and pointed to by the variable NEMPTC. Similarly a list of redundant doubles is headed by the variable NEMPTD. The variable NEMPTG points to the first word in free (unused) memory.

The concept of a pre-formed empty list stretching to the end of memory, as used in RBM, has been discarded for RBMC; free memory is unstructured.

4.3 INTRODUCTION OF A CRACK INTO A BLOCK

The basic assumptions that have been made in the present version of RBMC are that:

i) a crack forms instantaneously, and splits the block concerned into two;

ii) the decision to create a crack in a block is based solely on the known forces acting on the block.

The process of cracking in the present context has two aspects, the numerical and the physical; each is treated separately below.

4.3.1 NUMERICAL ASPECTS OF CRACKING

When the decision is made to crack a block, the following sequence of events occurs:

(i) The two contacts (between which the crack will extend) are broken (i.e. the forces that were acting vanish).

(ii) The basic data array and pointer for one new block is created.

(iii) Four new corners are created, and, together with the existing corners, are linked up to form the two new corner lists for the two blocks.

(iv) Areas, masses, moments of inertia and centroids are computed for the two blocks, and written into the appropriate data arrays.

(v) Contacts (other than those that produced the crack) that existed around the single original block are transferred to one or other of the two resulting blocks. The contact forces are retained, but a re-numbering and re-linking is necessary.

(vi) Box entries for the original block are converted to box entries for the created block where appropriate.

(vii) A new problem time-step is computed for the whole array of blocks.

4.3.2 PHYSICAL ASPECTS OF CRACKING

Almost any criterion for cracking may be incorporated in the program with little difficulty; in fact several schemes may be used together. The description that follows corresponds to the particular scheme that is contained within RBMC at present. It is based on the tensile cracking

that occurs when more or less point loads are applied on opposite sides of a rock block. In its ideal form, this type of approach constitutes the "Brazilian test" (Fairhurst, 1964) and is performed with a disc of rock loaded between flat plattens. More generally, many "point load tests" have been performed in which irregular or regular blocks of rock are loaded between two indentors that may have small radii of curvature. Such tests have been described by Franklin & Broch (1971), Broch & Franklin (1972) and Brook (1977), and are characterised by a failure load that is related to the distance between the points of application of the loads, and a "strength" that is supposed to be constant for a given material. The relationship for fracture is:

$$S = \frac{KP}{h^2}$$

Where h is the distance between applied loads, P;

K is a factor that depends on the shape of the block;

S is a rock strength, supposedly constant.

In program RBMC, each block is scanned for the maximum two forces, P_1 and P_2 that are being exerted on the block by corners from other blocks (the forces that are being applied by the <u>edges</u> of other blocks are not taken into account). The average is then taken, divided by the distance squared, and compared to a user-specified "strength", S': i.e.

$$\text{Crack formed} \xleftarrow{\text{yes}} \text{is } \frac{\tfrac{1}{2}(P_1 + P_2)}{d^2} > S' \text{ ?} \xrightarrow{\text{no}} \text{no crack formed.}$$

The crack is rejected if either:

(i) d is too small (<1 unit at present)

(ii) the applied forces are too close to existing corners (<2 units at present).

Once a crack has been accepted, the logic described in Section 4.3.1 is used to introduce it into the block concerned.

4.3.3 USE OF ALTERNATIVE CRITERIA FOR CRACKING

The cracking criterion is applied in subroutine CRACK, which is called for each block at every time-step if there are two or more suitable contacts on the block. The user has available to him a list of those contacts that correspond to corners of other blocks touching the block under consideration. It is up to the user to decide if the block will crack, and if so, which two contacts are involved. He then passes the addresses of these two contacts to subroutine *SPLIT*, which deals with the housekeeping tasks necessary to form the crack.

The list of contacts referred to above is available to the user as a simple array in free memory, and takes the form of a set of pointers to the relevant contacts. The first pointer is contained in location NEMPTG in the array A, and the last pointer is contained in location NEMPT. Access may be made to any of the data stored for each contact (the format is given in Figure 4.4).

If it has been established that a crack will be formed, the pointers to the two contacts involved must then be passed to subroutine SPLIT, as follows:

```
CALL SPLIT (IC1,IC2),
```

Where IC1, IC2 are the addresses of the two contact data arrays.

4.4 USE OF PROGRAM

Program RBMC is used in the same way as RBM, with almost the same set of commands. However, density is now a global variable, and is specified when setting up a new problem. The "strength", S, described in Section 4.3.2 is also specified in the same way. Consequently the following commands are now added to those of data set number 1:

DENSITY	RHO	Defines the density for all blocks (A10,F10.0)
TSTRENGTH	S	Defines the cracking "Strength" S, described in Section 4.3.2 (A10,F10.0)

The create command in data set number 2 has been changed slightly to eliminate the specification of density:

CREATE	NC,IFIX	(A10,2I10) Creates a block with NC corners. IFIX $\neq$ 0 for a fixed block. This command is followed in the usual way by a list of corner coordinates.

Apart from these changes, the input stream is identical to that for RBM.

The output format is also very similar, except that the program prints a message informing the user whenever a crack occurs. The coordinates of the crack are printed, together with the new time-step if this differs from the old time-step.

4.5 EXAMPLE RUNS

It was not within the scope of the present study to perform extensive validations on the program; rather, the object of the example runs was to verify that the modified logic worked as intended.

4.5.1 NON-CRACKING TESTS

Validations 5 and 6 described in Chapter 2 (block on plane; Goodman & Bray toppling) were run using RBMC with a high strength in order to inhibit cracking. Identical results were obtained, showing that the translation from local to global coordinates was correct, and that the modified boxing and updating logic was working.

4.5.2 TEST 1: 3-BLOCK PROBLEM

Figure 4.5 shows a case in which a single crack is induced in a block loaded above and below by wedge-shaped blocks. The lower block is fixed, and the other two blocks are acted on by gravity, with the system starting from the state shown with zero velocity. The subsequent movements of the blocks are shown for four values of the coefficient of friction.

4.5.3 TEST 2: 7-BLOCK PROBLEM

This test is more complex and provides a searching test of the logic concerned with cracking, contact detection, re-linking lists and

re-boxing entries. The pile of blocks shown in frame 1 of Figure 4.6 are suddenly acted on by gravity from an initial state of zero velocity. The "rock" has very low strength, so that the subsequent frames (Figs. 4.6 & 4.7) show the ends of the blocks breaking off, and then secondary and tertiary fractures as these pieces strike other blocks. The properties for the run were as follows:

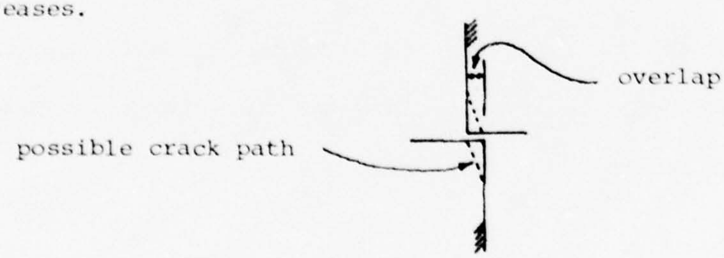
Density:	1.0
"Strength", S:	100.0
Mass of largest block	6000.0
Gravity	-10.0
Contact Stiffnesses	1.0×10^7
Damping (stiffness-proportional)	0.25 at frequency 30.0
Coefficient of friction	0.2
Fraction of critical timestep	0.1

Frames 1 through 10 are plotted at 400 cycle intervals, and frames 11 through 15 are at 800 cycle intervals, since the time-step was reduced when the tiny block was created in frame 10.

4.6 CONCLUSIONS

The data structures and internal housekeeping logic of RBM have been changed considerably to allow cracks to form across blocks. After a block has cracked, the two resulting parts become independent blocks, which can then interact with other blocks in the normal way, and subsequently crack again should conditions permit. Although only a simple criterion for crack formation has been tried so far, the program is written in a way that makes the incorporation of alternative criteria a simple matter. The type of cracking that is permitted at present corresponds to fractures of the type observed in point-load tests.

Corner-cracking, in which a single force near a corner causes the corner to break, has been discussed but not implemented. It appears that the present scheme may not be the best way to overcome the problem of "locking-up" caused by very slight overlap of block corners. The argument runs as follows: the "strength" of a corner will reduce as the overlap decreases.



Consequently even an infinitesimal overlap will cause a crack to form, since the force required will be vanishingly small. An initially sharp-cornered block will acquire several very small extra faces that will

increase the computation time considerably, but will hardly modify the subsequent physical performance of the block. The extra faces will not even guarantee that close encounters with future corners will be trouble-free, since additional tiny chips may break off, in view of the very small strength noted earlier. It may be better to consider other ways of overcoming the "locking-up" problem that are physically equivalent to corners breaking, but do not carry the high computational overhead involved in creating new faces. For example corner-to-corner contacts could be made especially deformable, so that two corners would literally "deform through" each other if the driving force were high enough. Even though such schemes would require more development work, the program RBMC will provide a good starting-point, since the data structures are arranged in a much more convenient way than RBM.

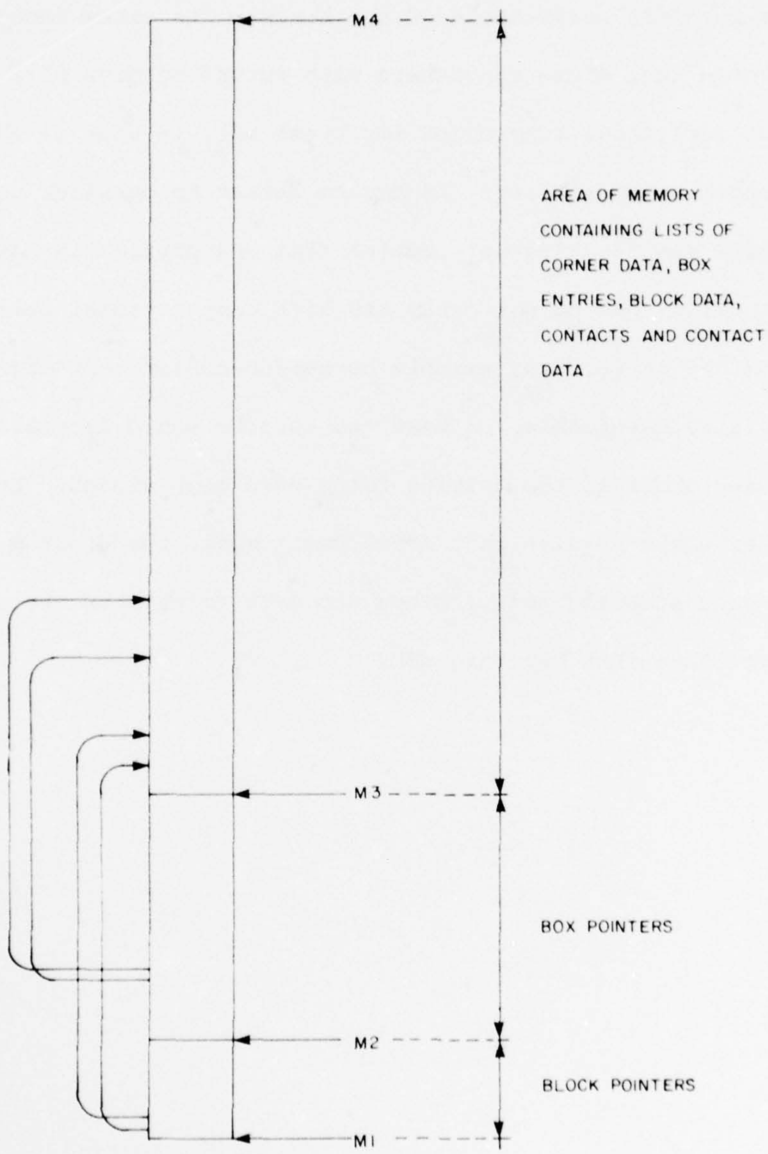


FIG. 4.1 MEMORY ALLOCATION FOR DATA LISTS

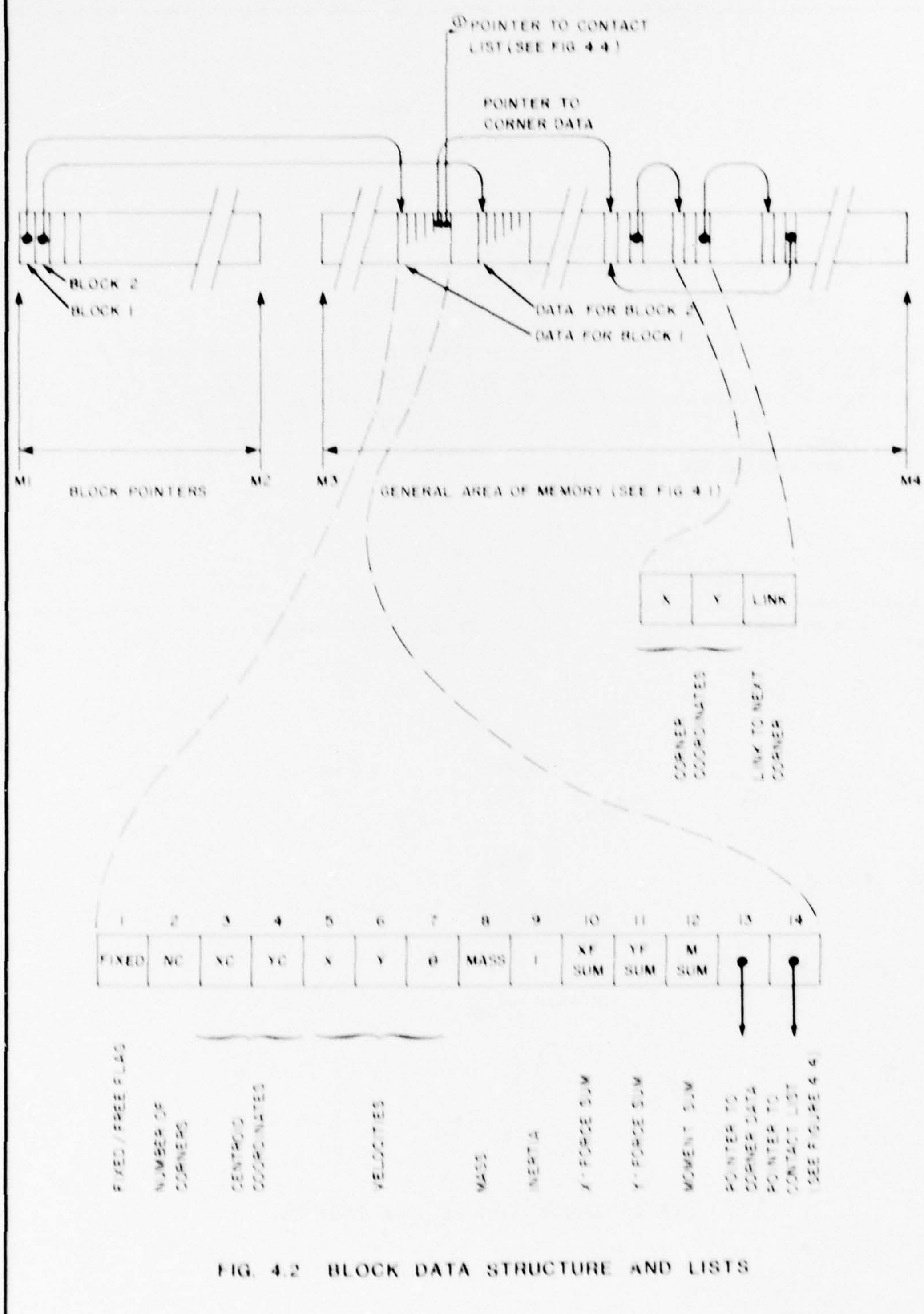


FIG. 4.2 BLOCK DATA STRUCTURE AND LISTS

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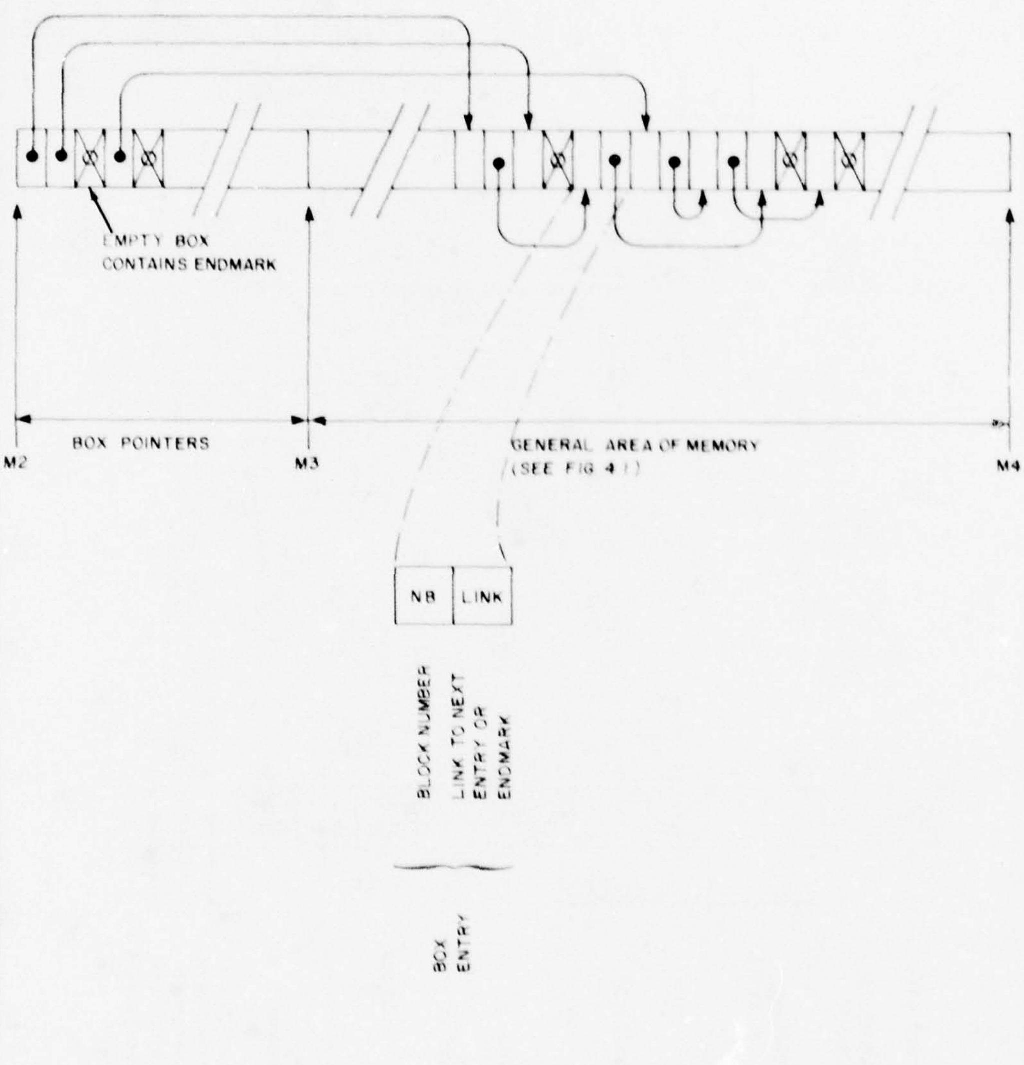

FIG. 4.3 LINKED LIST OF BOX ENTRIES

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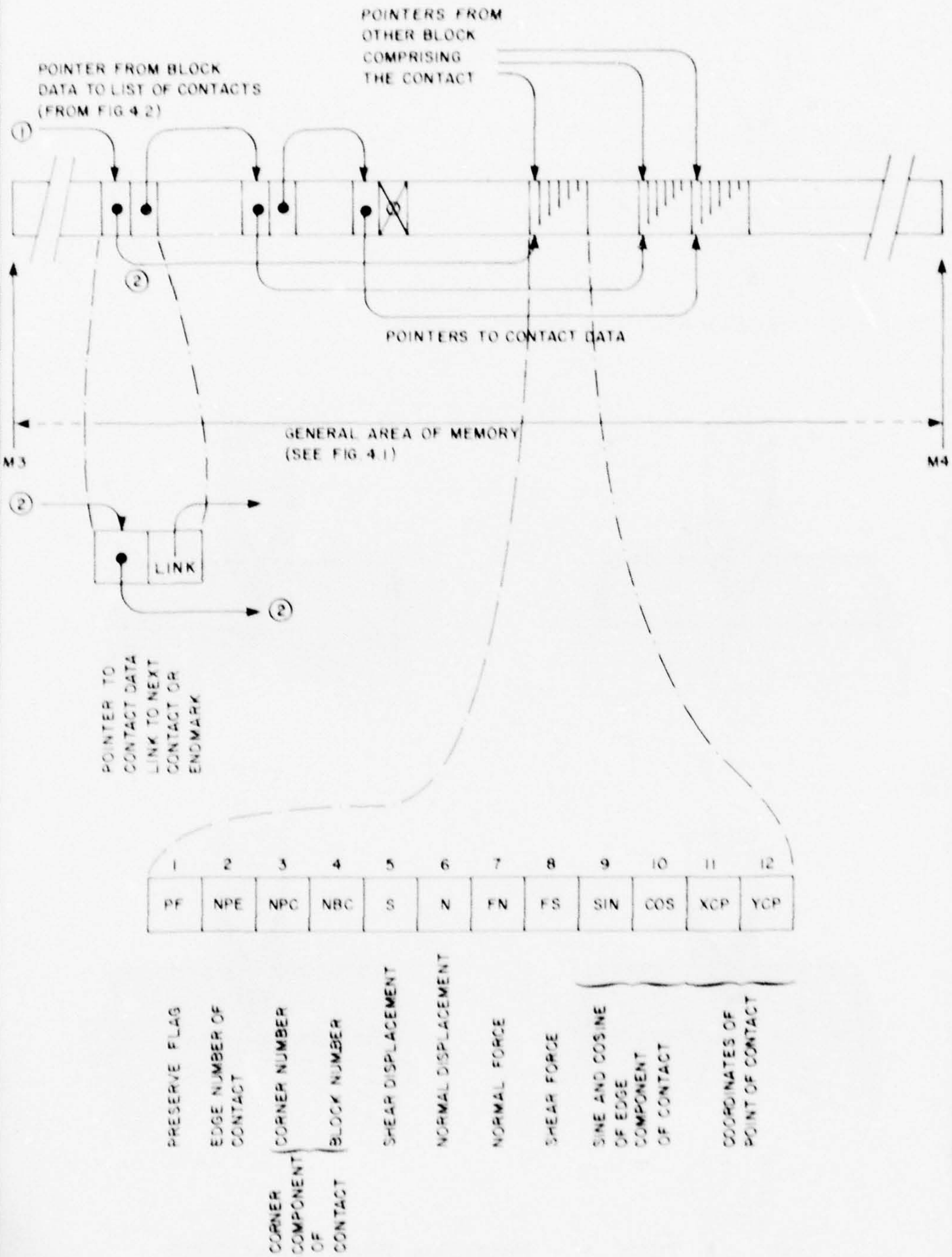


FIG. 4.4 CONTACT DATA STRUCTURE AND LISTS

DAMES & MOORE

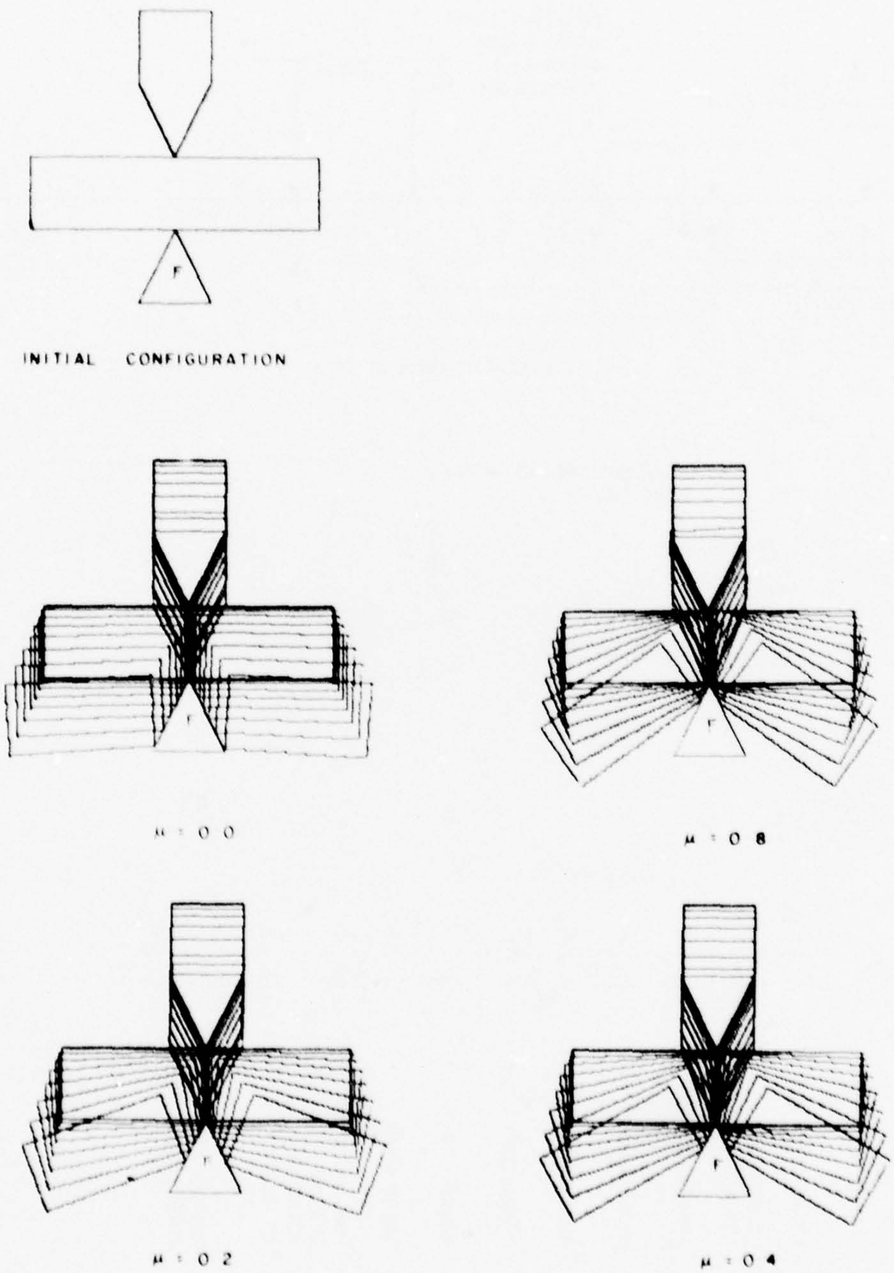


FIG. 4.5 TEST 1 - PROGRAM RBMC BEHAVIOUR FOR VARIOUS FRICTION COEFFICIENTS IS SHOWN.

DAMES & MOORE

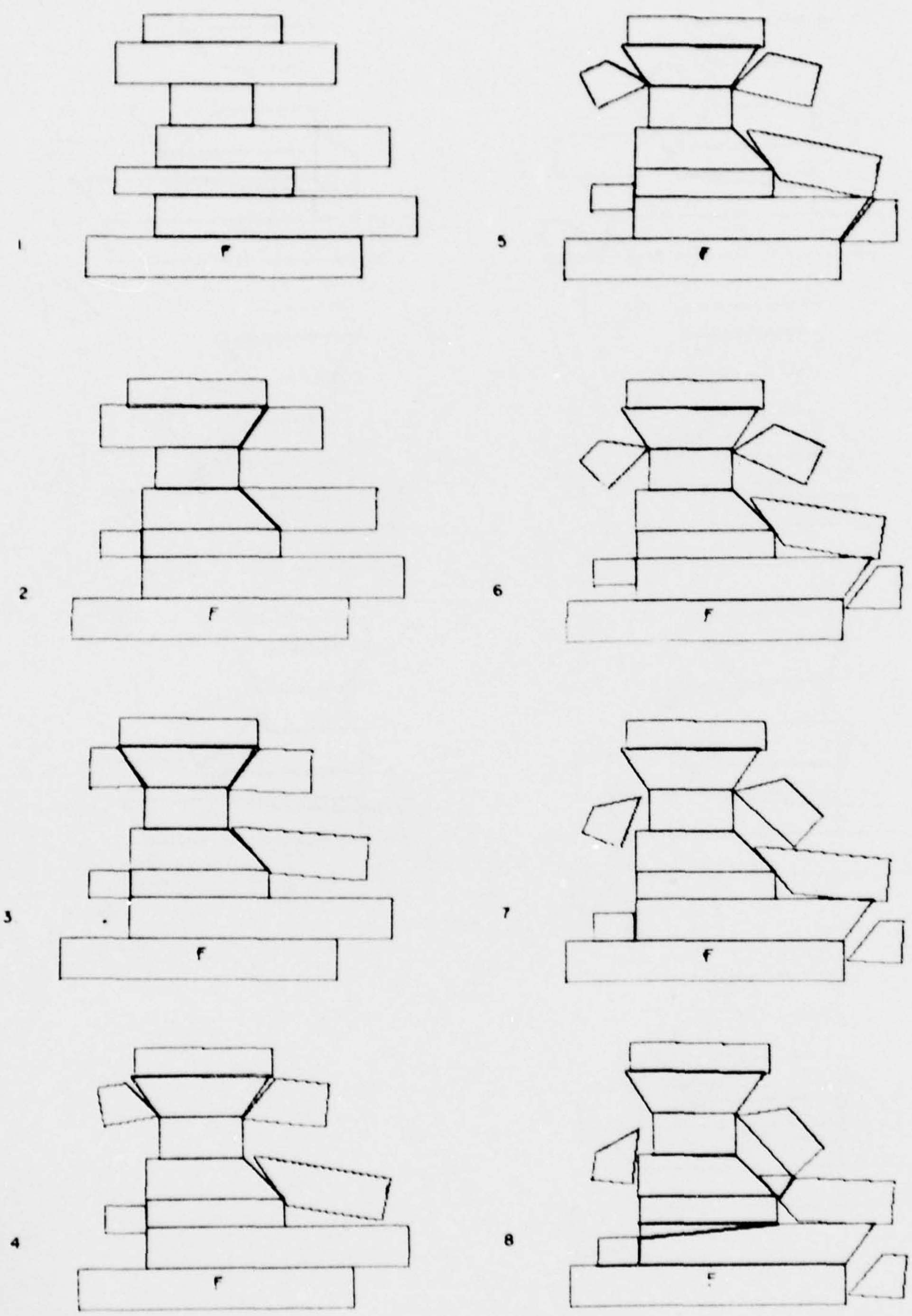


FIG. 4.6 TEST 2 OF PROGRAM RBMC

DAMES & MOORE

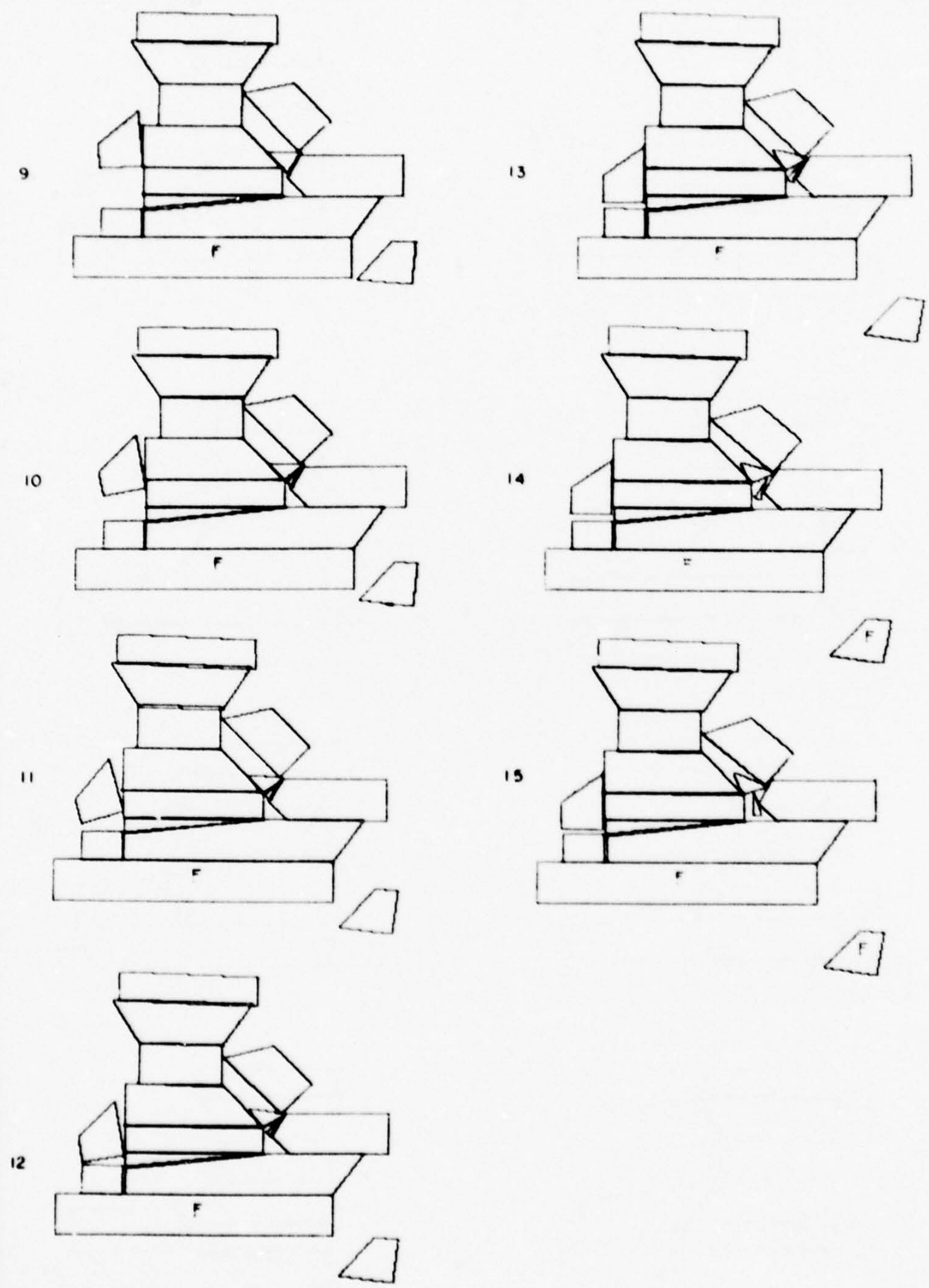


FIG. 4.7 CONTINUATION OF TEST 2

CHAPTER 5: BEHAVIOUR OF ROCK JOINTS

5.0 *A literature survey is presented on the results from laboratory and field tests on rock joints. The information from the survey is used to develop a simple constitutive law for rock joints.*

5.1 INTRODUCTION

Rock joints are surprisingly complex. They dilate and contract with shearing; their apparent coefficient of friction changes drastically with normal stress and with the history of shearing displacements; their behaviour is sensitive to any filling material, and whether or not it squeezes out during shearing. Any constitutive law must take account of these effects if it is to be realistic.

A bibliography has been assembled on rock joints, and covers laboratory tests, field tests and theories of behaviour. A few references have also been included on numerical and physical models of jointed rock. The next section highlights some of the results from the literature and demonstrates the range of behaviour that is exhibited by rock joints. Based on this information, a simple constitutive law for joints is developed.

The papers referred to in the next section are located in the bibliography of Appendix II, and selected plots from these papers are reproduced at the end of this Chapter.

5.2 LITERATURE SURVEY

Pore water, surface roughness, normal stress, degree of weathering, joint infilling, joint orientation, joint spacing, normal stress and rate of shearing all affect the behaviour of jointed rocks.

Rock joint properties under a variety of conditions have been measured. For example, Iida (1974) ran insitu loading tests on a jointed rock foundation and compared the recorded strains with strains obtained from elasticity equations (see Figure 5.1). Krsmanovic and Popovic (1966a) studied the insitu behaviour of fissured limestone with various degrees of joint infilling. Gale (1975) studied fracture flow in deformable rocks and and found that injection and withdrawal are non-reversible processes, which implies that there must be hysteresis in the normal direction of loading.

Direct shear with controlled normal loads and triaxial compression are two of the most common tests used to study jointed rock properties. Shear stress vs. shear displacement, and normal displacement vs. shear displacements are typically recorded during a direct shear test (see Figure 5.2). Repeated loadings and unloadings may be prescribed and the normal load may be changed several times during the test (see Figure 5.2). During triaxial compression tests, the principal stresses vs. axial displacement are recorded (see Figure 5.3). Pore pressure measurements may be recorded during both shear and compression tests.

Triaxial failure envelopes may be linear or curvilinear (see Figure 5.4). Jaeger (1959) found dry granitic gneiss to give reasonably linear failure envelopes and yet when the samples were soaked in water just prior to testing, the failure envelopes usually showed considerable curvature.

Some rocks dilate linearly during extensive shearing but commonly compact initially (see Figure 5.5). Martin and Millar (1974) reversed the shearing direction in the middle of direct shear tests and found the greywacke samples first to contract and then to dilate (see Figure 5.6).

Shear stress vs. shear displacement curves generally fall into two classifications. Some jointed rocks are stiff during initial shearing, reach a peak value of shear strength which then drops off rapidly, and finally taper off in strength to some residual value (see Figure 5.7a). Others exhibit elastic behaviour during initial shearing and then behave more or less plastically with little or no distinct peak (see Figure 5.7b). The slope of the elastic portion of stress-displacement curves has been designated by Goodman, Taylor and Brekke (1968) as the shear stiffness. For example, the shear stiffness of garnet schist with quartz beds (see Figure 5.7) equals $10.4 MN/m^2 cm$. Values obtained from various shear tests are tabulated in Table 5.1. The type of stress-displacement curve is greatly influenced by the shear surface roughness and the joint infilling properties of the joint. For example, Krsmanovic, Tufo, and Langof (1966b) found

the presence of clay infilling material to change the shape of the stress-displacement curve for fissured limestone (see Figure 5.8). Jaeger (1971) recorded dramatic changes in the shear behaviour of bowral trachyte upon wearing of the shear surface (see Figure 5.9). Kutter (1974) also found reshearing to modify the shear stress-shear displacement curve (see Figure 5.10). These changes can be related to the selective destruction of the asperities present on both rock faces.

Using plaster models, Patton (1966b), Krsmanovic et. al. (1966b) Barton (1971c), Schneider (1974) and others have studies how asperities control shear at different normal loads. Patton (1966) and Krsmanovic et. al (1966) sheared plaster models across planes having teeth of various inclinations and frequencies. At low normal stresses, Patton found the effective angles of friction to equal the internal angle of friction of the plaster plus the asperity angle (see Figure 5.11). At high normal stresses, Patton found the asperities to be sheared off and the effective angle of friction to equal the internal angle of friction of the plaster (see Figure 5.11). Barton (1971c, 1974) statistically analysed several hundred direct shear tests run on plaster and jointed rocks: he found the following relationship between the peak shear strength, the surface roughness and the normal load:

$$\tau/\sigma_n' = \tan\left\{ JRC{*}\log_{10}(JCS/\sigma_n') + \phi_b \right\}$$

where τ = peak shear strength

σ_n' = effective normal stress

JRC = joint roughness coefficient

JCS = effective joint wall compressive strength

ϕ_b = base friction angle

Schneider (1974) sheared plaster samples cast from granite, limestone, and sandstone samples. Dilation curves, shear stress-shear displacement curves, and shear stress-normal stress curves for the three surface types vary considerably (see Figure 5.13). These results are interesting because they show how the roughness alone affects the behaviour, for identical intact material strength. (See Figure 5.13).

Patton (1966a) recognised that two scales of roughness govern the shear behaviour of rocks (see Figure 5.14). The behaviour during small displacements and the large second order irregularities govern the shearing behaviour for large displacements.

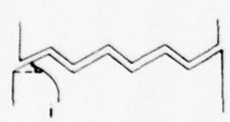
In general it can be said that at low normal loads, the behaviour of the joint will be influenced by the highest-angle (smallest) asperities while at higher normal stresses, these asperities will be sheared off, so that the longer, lower-angle asperities will be the major influence. This type of behaviour must be recognised by any constitutive law for joints.

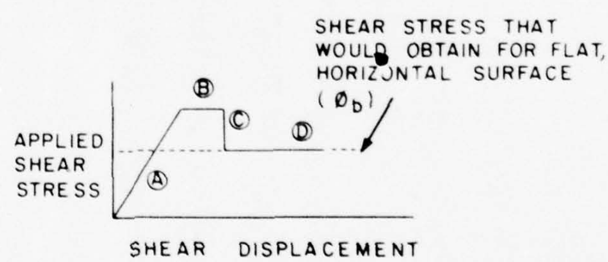
5.3 CONSTITUTIVE LAWS

The preceding discussion has shown that joint roughness plays a major part in the mechanical behaviour of joints. However, roughness is not a constant attribute, and account must be taken of the effects that changes in roughness produce, due to asperities being worn down or destroyed.

5.3.1 MECHANICS OF AN IDEALISED JOINT

As a preliminary to the development of a constitutive law, consider the mechanics of a simplified joint, with a single wavelength of asperity; and its idealised stress/displacement curve for a given normal load:

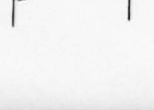


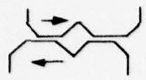


The various parts of the curve may be identified with the following mechanisms:

A. elastic straining - no slip

B. sliding up on asperities - apparent friction angle = $\varphi_b + i$, where φ_b = basic friction angle of the material.

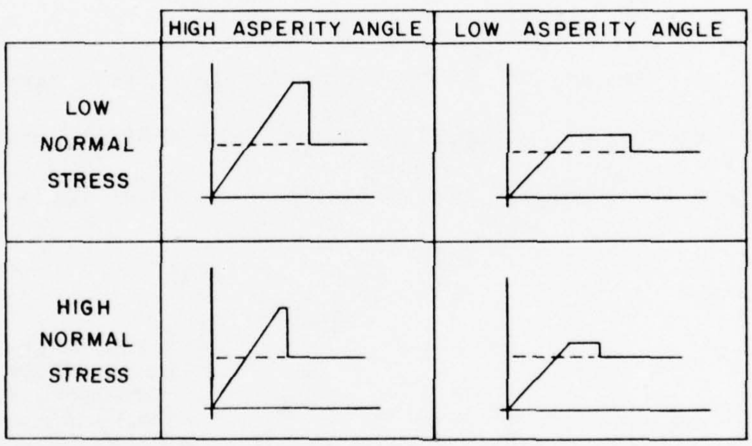




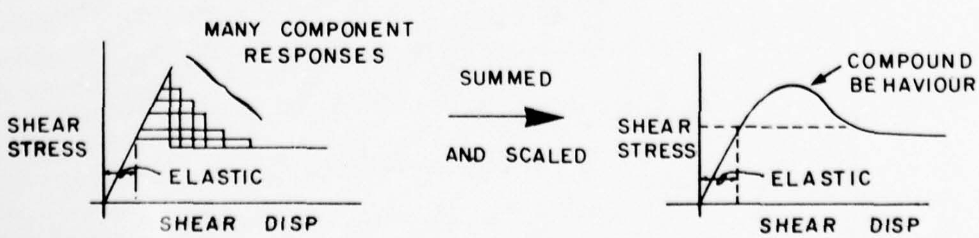
C. shearing off of asperity-tops

D. sliding on horizontal surfaces created by sheared asperities.

The curve shown above is modified for changes in asperity angle and normal stress:



Clearly, a real joint is made up of many sizes of asperity, so that the resultant stress/displacement curve is more or less a summation of many basic curves:



In conjunction with the shear behaviour described above, the joint also tries to dilate, the major part of which occurs during phase B - the sliding-up phase, characterized by the flat-topped part of the shear stress/displacement curve.

5.3.2 SIMPLIFIED BEHAVIOUR

At any stage during an arbitrarily-complex loading history, a joint will have some of its asperities sheared, while others (of longer wavelength) will be intact. Of the asperities that have been sheared, some will have only their top parts broken, but others may be almost completely destroyed. In order for a numerical scheme to be able to model completely the mechanics of such a system, a memory would be needed of the proportion of each size of asperity that had been destroyed at any given time. Clearly, such computer storage requirements would be impracticable and indeed unwarranted, given the very limited experimental data on rock joints.

An alternative, approximate, approach will be considered here that reproduces several of the observed characteristics of real joints, plus some effects that have not been the subject of testing, but could well be verified, or otherwise, in the future. Several of the concepts used in what follows are due to Barton (see, for example, Barton and Choubey, 1978).

Before developing the constitutive law, several (perhaps obvious) points will be stated:

1) The peaks (or "bumps") on shear stress/displacement curves are caused by asperities.

2) Shearing removes asperities and causes damage to the joint surface.

3) The damage is greater for greater σ_n (normal stress) and for increasing U_s (shear displacement).

4) If a joint is sheared at very low σ_n, it will be almost undamaged; consequently, its subsequent shearing behaviour for high σ_n will hardly be affected, except that the shear stress/displacement curve will be displaced bodily by the amount of low-σ_n shearing. (This ignores the possibility that mating joints become non-mating.)

These points lead to the concept of a variable, D, that accumulates the damage done to the asperities during shearing. Clearly there is no unique way to define D, since it is an approximate measure anyway, but as a first attempt, consider the following expression:

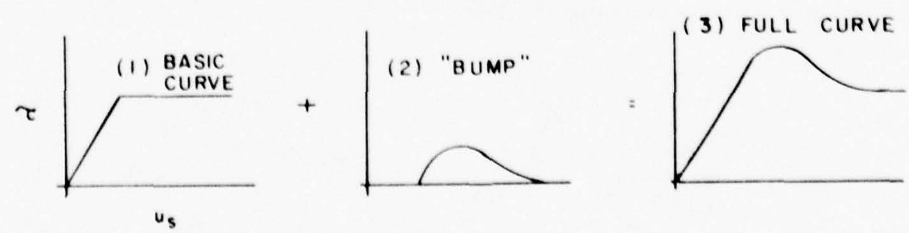
$$D = \Sigma \, \sigma_n \Delta U_s \quad \text{, where}$$

the sum is performed for all loading increments during which the shear stress is above the residual.

This expression satisfies the obvious conditions that D must vanish for either $\sigma_n = 0$ or $\Delta U_s = 0$. It may be normalised if necessary to the range $0.0 < \bar{D} < 1.0$ by dividing by the maximum normal stress times the maximum shear diplacement for residual strength under that normal stress:

$$\bar{D} = \frac{\Sigma\, \sigma_n \Delta U_s}{\sigma_n^{(jcs)} U_s^{(max)}}$$

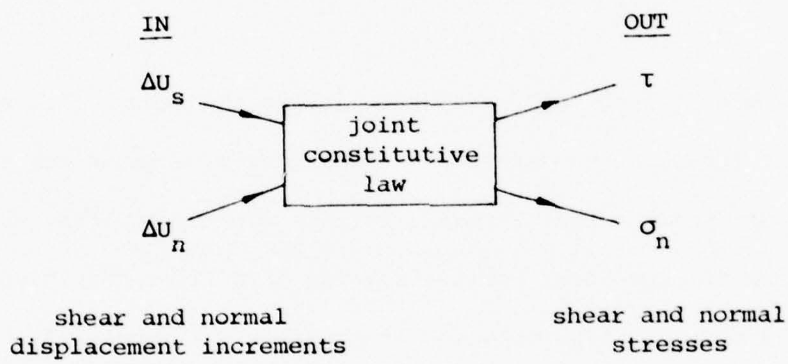
The main utility of D is that it allows the damage done at one value of normal stress to be carried over and used as a basis for subsequent shearing at a different normal stress. This is done by shifting the shear stress/displacement curve over until its value of D (i.e. the value of D that would have obtained from shearing at constant σ_n) equals the current accumulated D. The shear stress/displacement curve referred to above is actually that part of the full curve that lies above the residual-strength part: i.e. only the "bump" of the full curve is stored, for the purpose of computation.



It is the "bump" that reflects the effects of the asperities; after all asperities have been removed, only the basic curve, (1), remains.

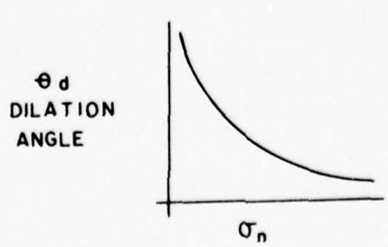
5.3.3 DETAILS OF CONSTITUTIVE LAW

In simplified form the proposed constitutive law for joints can be represented by the flow diagram on the following page. Note that the constitutive law works from displacements to stresses:

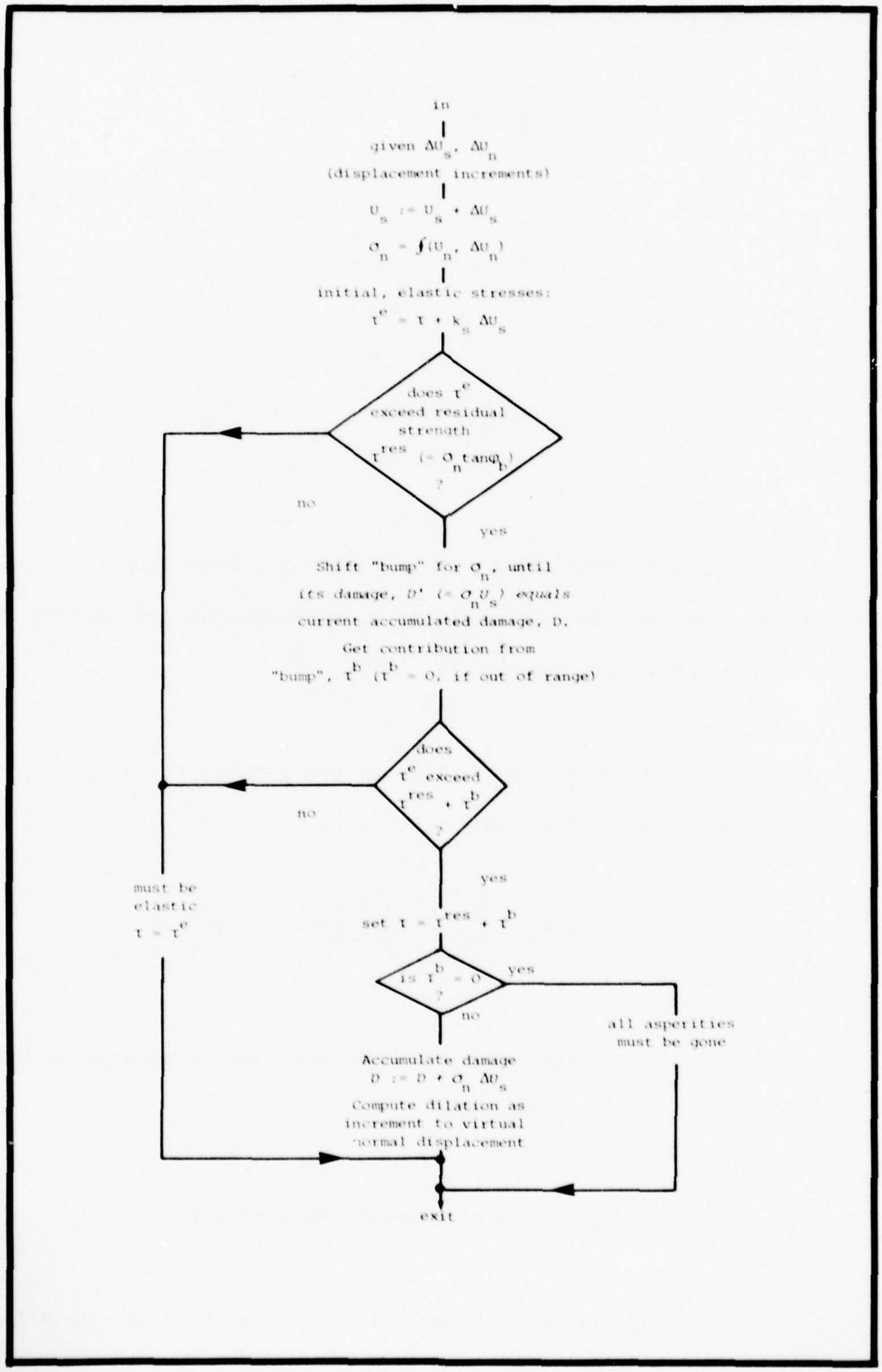


5.3.4 DILATION

Dilation is assumed to occur whenever damage is accumulated, according to some user-defined law. In general, the dilation angle is related inversely to the normal stress:



Since, in the explicit method, both displacements U_s and U_n are given, the dilation must be expressed as an equivalent increase in normal



in
given ΔU_s, ΔU_n
(displacement increments)
U_s := U_s + ΔU_s
σ_n = f(U_n, ΔU_n)
initial, elastic stresses:
τ^e = τ + k_s ΔU_s
does τ^e exceed residual strength τ^res (= σ_n tanφ_b) ?
no
yes
Shift "bump" for σ_n, until its damage, D' (= σ_n U_s) equals current accumulated damage, D.
Get contribution from "bump", τ^b (τ^b = 0, if out of range)
does τ^e exceed τ^res + τ^b ?
no
yes
must be elastic
τ = τ^e
set τ = τ^res + τ^b
is τ^b = 0 ?
yes
no
all asperities must be gone
Accumulate damage
D := D + σ_n ΔU_s
Compute dilation as increment to virtual normal displacement
exit

stress. This may be done as follows:

$$\Delta\sigma_n = \left(\frac{\partial\sigma_n}{\partial U_n}\right) \Delta U_n^d \quad \text{, where}$$

$\dfrac{\partial\sigma_n}{\partial U_n}$ is the current normal joint stiffness

ΔU_n^d is the incremental normal displacement due to dilation

In the plots given later, the dilation is shown directly as ΔU_n^d, but in use the constitutive law would use this displacement to modify σ_n according to the expression above.

The actual dilation law built into the program is based on Figure 5.12 (from Barton, 1971) and is given by:

$$\tan \Theta_d = \frac{\Delta U_n^v}{\Delta U_s} = \left\{ \frac{\sigma_{(jcs)}}{\sigma_n} - 1 \right\} k_d$$

k_d is the "dilation constant" and is prescribed by the user

$\sigma_{(jcs)}$ is joint compressive strength

ΔU_n^v is the virtual normal displacement due to dilation

Θ_d is the dilation angle.

Dilation, U_n^v , is only accumulated during periods when "damage", D, is being accumulated.

5.3.5 COMPUTER PROGRAM FOR CONSTITUTIVE LAW

The steps described above have been embodied in a computer subroutine, JOINT, which is listed in Appendix XV. The program is quite simple and is probably easier to follow than a written description of the procedure. All important variables are defined in the listing, but the following notes should be consulted before trying to understand the program:

1) The program is written in terms of normalised displacements and stresses.
"Real" stresses may be obtained by multiplying output stresses by $\sigma_{(jcs)}$, where $\sigma_{(jcs)}$ is Barton's "joint compressive strength".
"Real" displacements are obtained by multiplying internal displacements by $U_s^{(max)}$, where $U_s^{(max)}$ is the shear displacement at which the shear stress drops to residual for a test performed for $\sigma_n = \sigma_{(jcs)}$.

2) The basic curve for the "bump" on the shear stress/displacement curve is built into function FSS as a DATA statement. It comprises 10 intervals, with maximum value of 1.0 units, but is subsequently scaled according to σ_n using Barton's law (see note 3).

3) The peak shear strength is given by Barton's equation:

$$\tau = \sigma_n \tan\left[JRC \log_{10}\left\{\frac{JCS}{\sigma_n}\right\} + \varphi_b \right]$$

(see Section 5.2)

It should be remembered that φ_b is in degrees. JRC is input to the program via common block /FRIC/. Any other law can be substituted in FSS if desired.

4) The shear displacement at which the shear stress falls to residual is adjusted according to the law:

$$U_s^{(max)} = K\,\sigma_n ,$$

where K = 1.0 at present.

Any other law may be substituted.

5) At present dilation is not coupled up in such a way as to modify σ_n (see Section 5.3.4), purely for purposes of presentation of test results. The virtual normal displacement due to dilation (UND(JID)) is computed internally, but not used, except for display.

6) The normal stress/displacement function at present is linear, and is evaluated in Function FSN. Another law may be substituted.

7) The normal stress must lie in the range $0.0 < \sigma_n < 1.0$, otherwise errors will occur. No traps have been incorporated. Also inaccurate results may be expected for σ_n close to zero.

8) The dimension of 50 refers to the number of joints that can be handled -- JOINT has to remember stresses, displacements and damage for each joint.

5.3.6 EXAMPLE RUNS WITH SUBROUTINE JOINT

The following parameters were used in all example runs:

$\varphi_b = 30^\circ$	basic friction angle
$k_s = 1.0$	initial shear stiffness
$k_n = 1.0$	normal stiffness
$k_d = 0.1$	dilation constant
JRC = 60	joint roughness coefficient

As mentioned earlier, the basic shear stress/displacement curve was built into the program in a DATA statement in Function FSS. The listing should be consulted for the values that were used.

Five example runs are presented in Figures 5.14 to 5.18, and are more or less self-explanatory.

In particular, Run 5 shows that the stress/displacement curves look quite realistic for complex loading paths.

5.4 CONCLUSIONS

A first attempt has been made to develop a constitutive law that will handle the complex loading paths that occur when running computer simulations of jointed rock behaviour. Although the results look plausible, there is not sufficient experimental data from tests with complex paths to check the assumptions made. More data is needed for cases where normal stresses are varying during a test in which shear displacement follows a time history with repeated reversals.

The concept of "damage" is thought to be promising, and it is hoped that it will be refined in the future as more experimental results become available.

TABLE 5.1 SHEAR STIFFNESS VALUES

ROCK TYPE - TEST DESCRIPTION	SOURCE	NORMAL STRESS (MN/m^2)	MAXIMUM SHEAR STRENGTH IN ELASTIC REGION	MAXIMUM DISPLACEMENT IN ELASTIC REGION (cm)	SHEAR STIFFNESS ($MN/m^2/cm$)
QUARTZ DIORITE	PRATT ET. AL. (1974a) Fig.3 p.308	NOT GIVEN			
Joint Area=$142cm^2$			8.75	0.024	3.6×10^2
Joint Area=$5130cm^2$			1.40	0.12	1.2×10^1
WEATHERED GREYWACKE	MARTIN & MILLAR (1974) Fig.4 p.266	0.49	0.9	0.043	2.1×10^1
FISSURED LIMESTONE	KRSMANOVIC ET.AL. (1966b)				
(No Infilling)	Fig 3	3.6	2.45	0.038	6.5×10^1
(No Infilling)	Fig 3	1.9	2.45	0.077	3.2×10^1
(No Infilling)	Fig 3	1.12	2.15	0.115	1.87×10^1
(No Infilling)	Fig 3	0.15	0.665	0.150	4.4
(Clayey Infilling)	Fig 4	2.4	0.42	0.025	1.7×10^1
(Clayey Infilling)	Fig 4	1.6	0.34	0.021	1.63×10^1
(Clayey Infilling)	Fig 4	0.77	0.176	0.042	4.2
FISSURED LIMESTONE (Insitu Shear Test)	KRSMANOVIC ET. AL. (1966a) Fig. 3p.775	1.47	0.51	0.10	5.1
		0.49	0.51	0.065	7.9
		0.98	0.64	0.125	5.1
ATALAYA PORPHYRY (Sample No. 8)	KUTTER (1974) p.10				
(1st run)		0.86	1.36	0.15	9.1
(2nd run)		1.81	0.65	0.105	6.2

TABLE 5 : (Cont/d.)

ROCK TYPE - TEST DESCRIPTION	SOURCE	NORMAL STRESS (MN/m^2)	MAXIMUM SHEAR STRENGTH IN ELASTIC REGION	MAXIMUM DISPLACEMENT IN ELASTIC REGION (cm)	SHEAR STIFFNESS ($MN/m^2/cm$)
DARLEY DALE SANDSTONE (Sample No.1)	KUTTER (1974) P.14				
(1st Run)		1.40	1.05	0.29	3.6
(2nd run)		1.38	1.05	0.29	3.6
(3rd run)		1.34	0.71	0.23	3.1
DELABOLE SLATE (Sample No. 1)	KUTTER (1974) P.32				
(1st run)		0.66	0.57	0.18	3.1
(2nd run)		0.668	0.273	0.097	2.8
(3rd run)		1.32	0.161	0.064	2.5
SCHISTOSE BANDED HEMITITE QUARTZITE	KUTTER (1974) p.39	0.979	1.04	0.25	4.2
GARNET SCHIST WITH QUARTZ BEDS (Sample No. 5)	KUTTER (1974) p.41	5.54	3.8	0.64	5.9

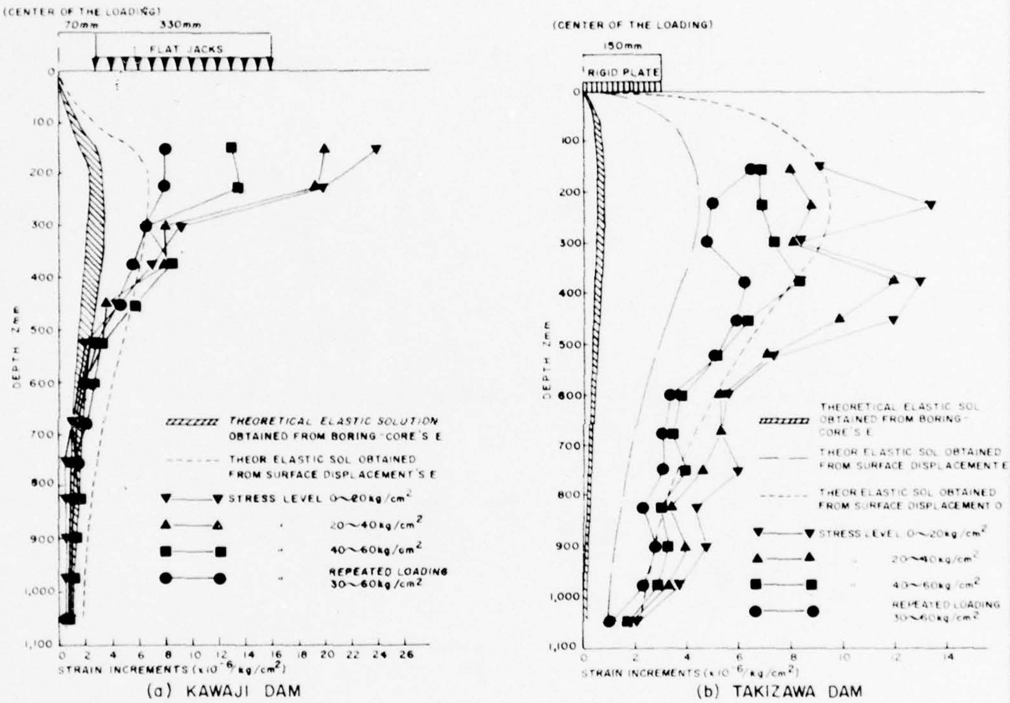


FIG 5.1 RECORDED STRAINS IN JOINTED ROCK VERSUS

STRAINS OBTAINED FROM ELASTICITY EQUATIONS

(AFTER IIDA, HOJO AND HARADA, 1974)

DAMES & MOORE

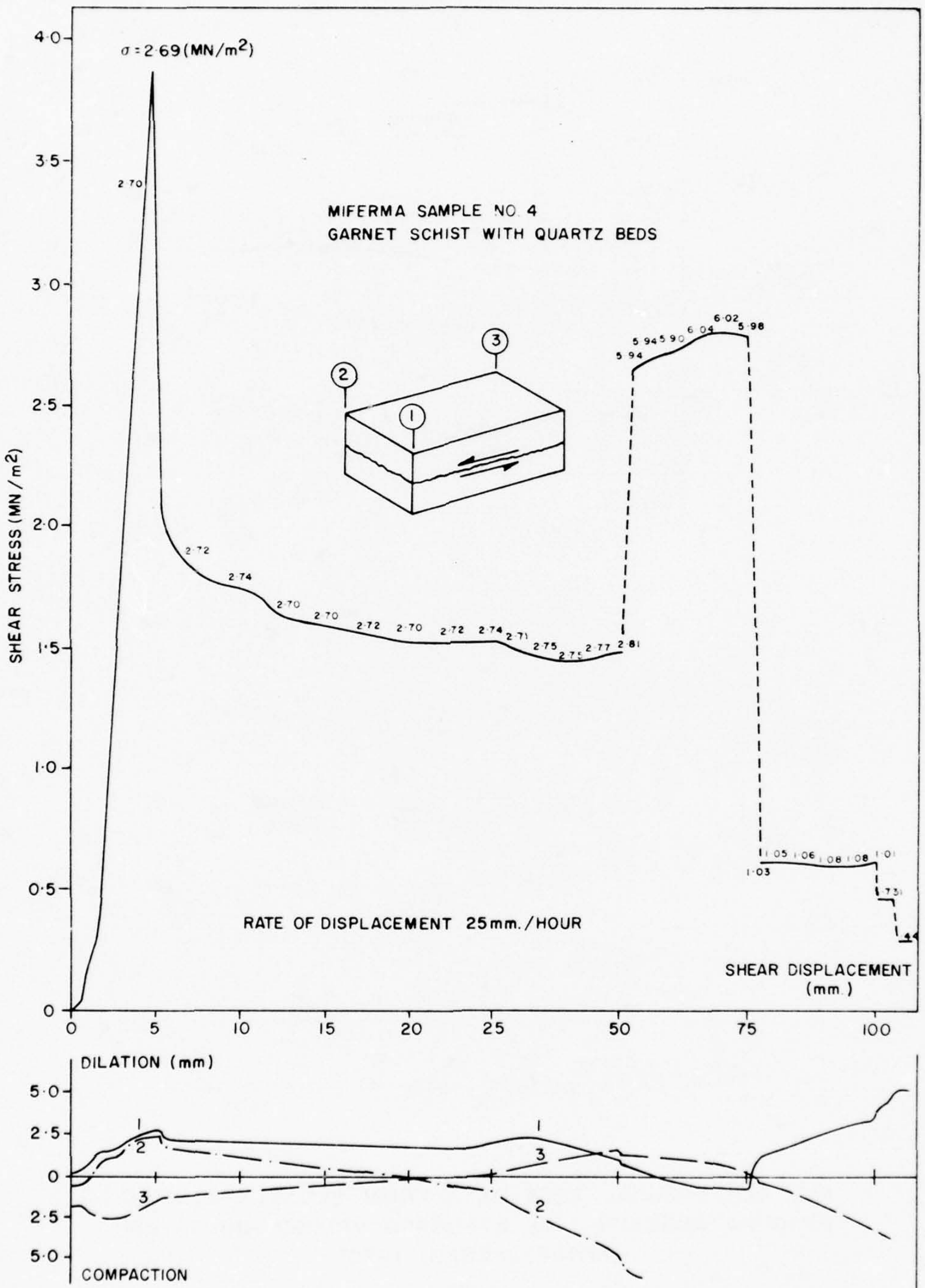
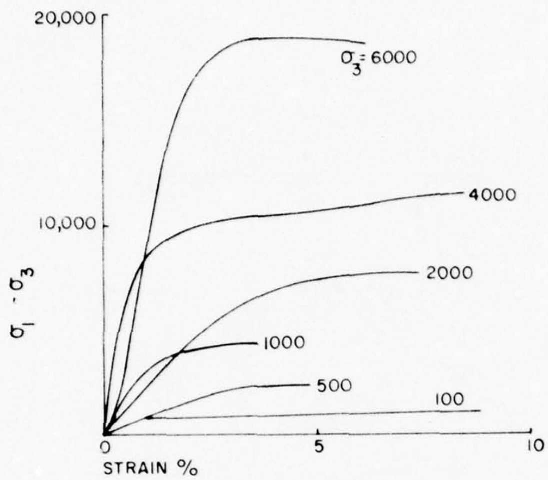


FIG. 5.2 DIRECT SHEAR TEST DATA (AFTER KUTTER, 1974)
NOTE CHANGES IN NORMAL LOAD DURING THE TEST

DAMES & MOORE



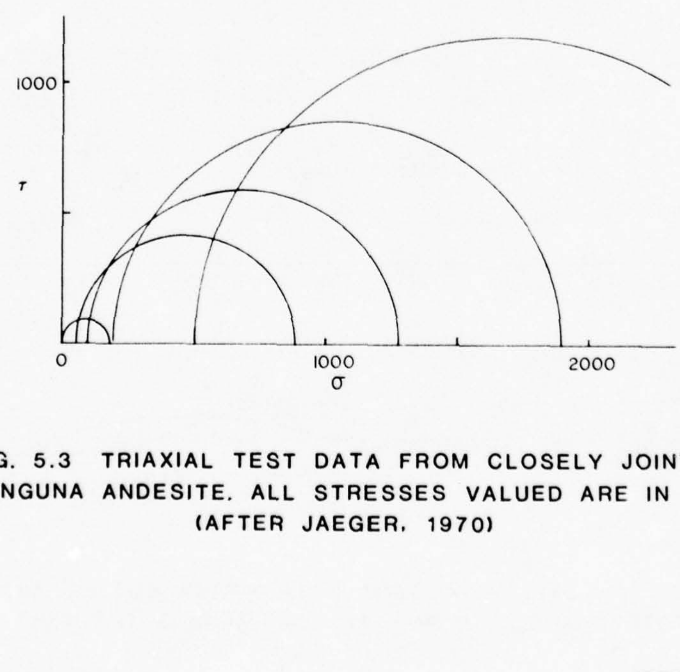


FIG. 5.3 TRIAXIAL TEST DATA FROM CLOSELY JOINTED PANGUNA ANDESITE. ALL STRESSES VALUED ARE IN PSI (AFTER JAEGER, 1970)

DAMES & MOORE

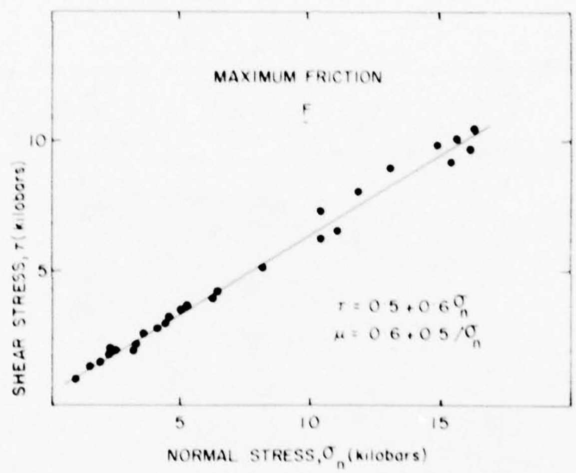


FIG. 5.4A SHEAR STRESS VERSUS NORMAL STRESS FOR FRACTURED GRANITE SPECIMENS FAILED IN TRIAXIAL COMPRESSION TESTS (AFTER BYERLEE, 1967)

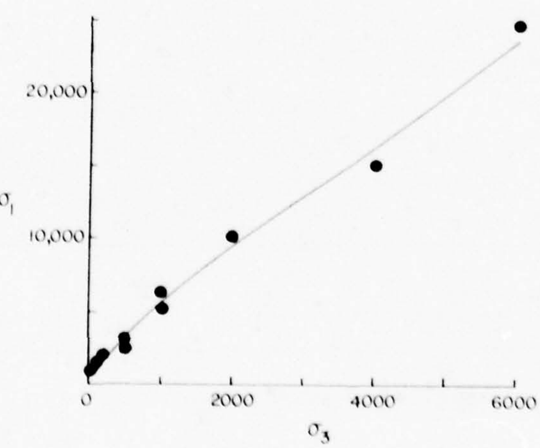


FIG. 5.4B SHEAR STRESS VERSUS NORMAL STRESS FOR 6 INCH CORES OF CLOSELY JOINTED PANGUNA ANDESITE (AFTER JAEGER, 1970)

DAMES & MOORE

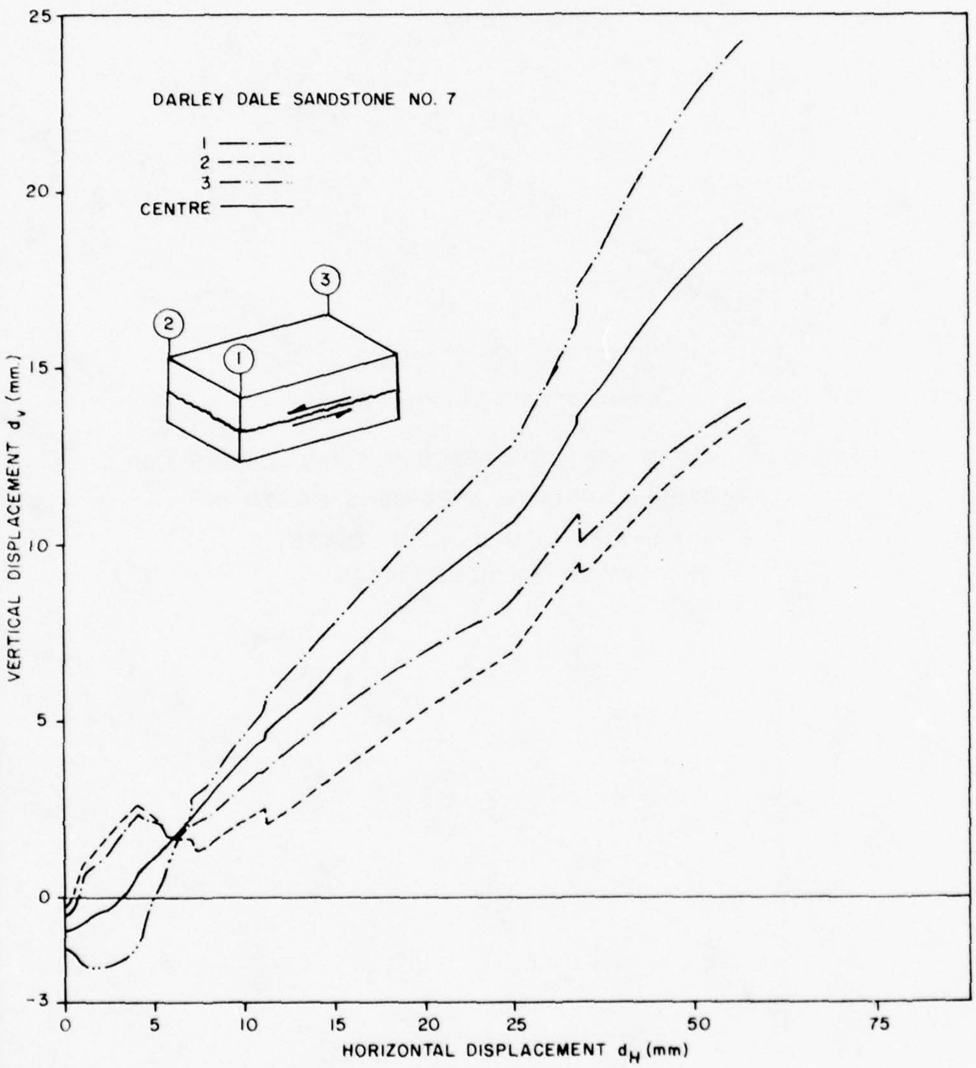


FIG. 5.5 DILATION CURVES FOR DARLEY DALE SANDSTONE (AFTER KUTTER, 1974)

DAMES & MOORE

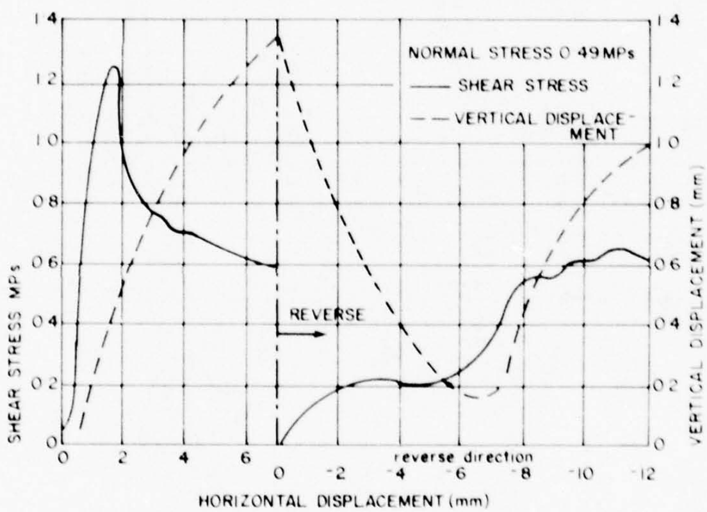


FIG. 5.6 DIRECT SHEAR DATA ON WEATHERED GREYWACKE (AFTER MARTIN AND MILLAR, 1974) NOTE THE CHANGE IN THE DILATION UPON REVERSAL OF THE SHEARING DIRECTION

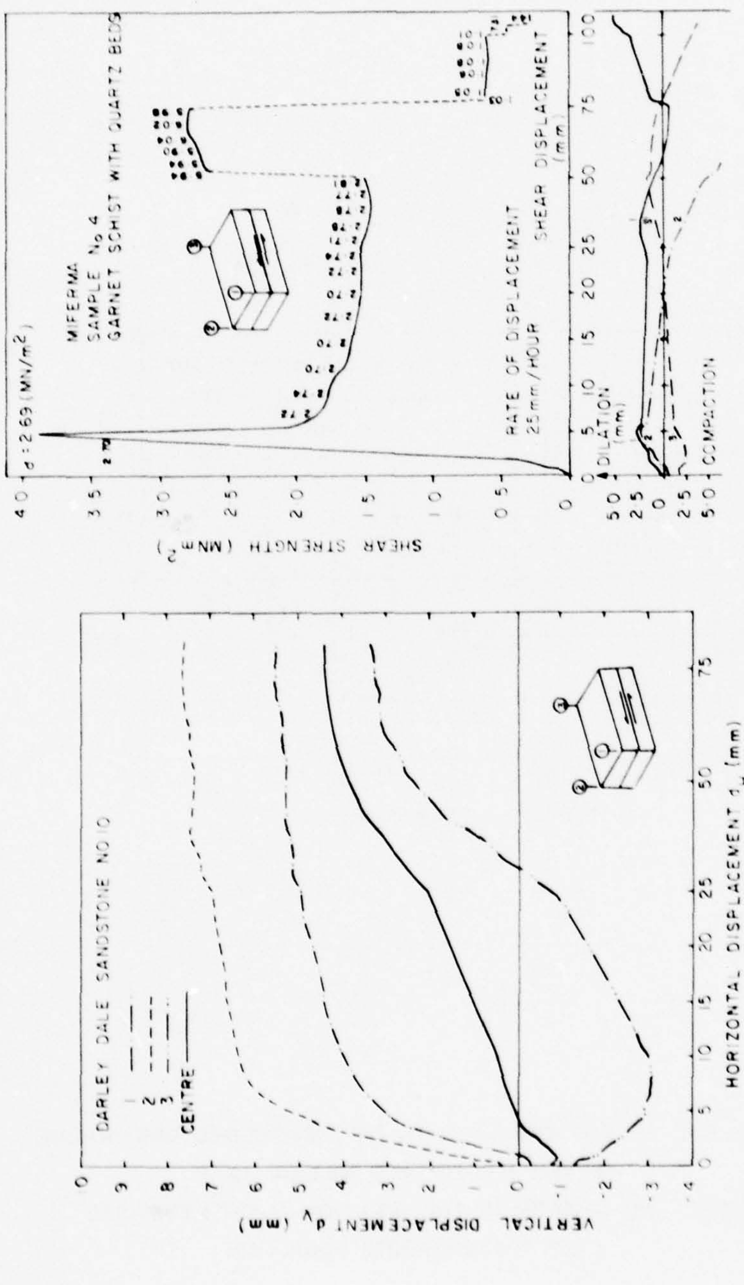


FIG. 5.7 DIRECT SHEAR DATA (AFTER KUTTER, 1975)

DAMES & MOORE

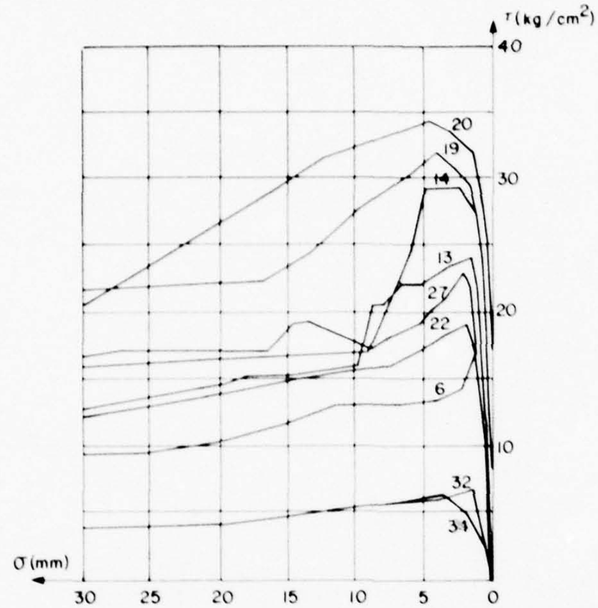


FIG. 5.8A DIRECT SHEAR DATA ON FISSURED LIMESTONE. WITH NO FILLING MATERIAL (AFTER KRSMANOVIC, TUTO AND LANGOF, 1966)

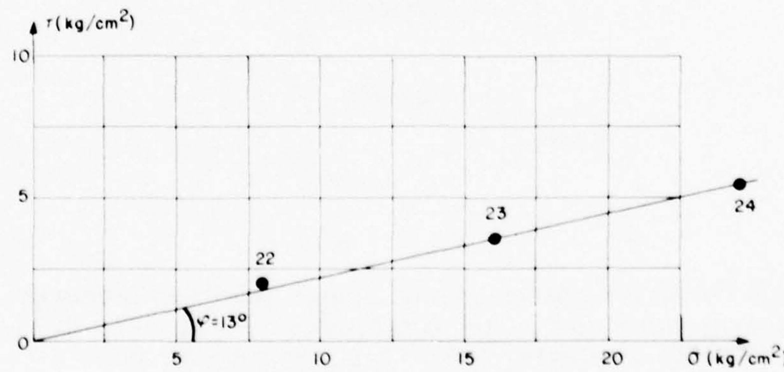


FIG. 5.8B DIRECT SHEAR DATA ON FISSURED LIMESTONE. WITH CLAYEY INFILLING MATERIAL (AFTER KRSMANOVIC, TUTO AND LANGOF, 1966)

DAMES & MOORE

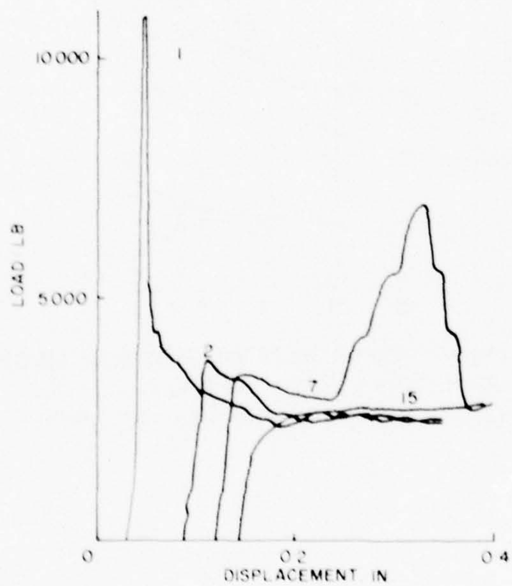


FIG. 5.9 VARIATION OF FRICTIONAL FORCE WITH DISPLACEMENT AND WITH WEAR FOR A SURFACE OF TENSILE FRACTURE IN BOWRAL TRACHYTE: AREA 5.2 SQ. IN.: NORMAL LOAD 1350 LB. NUMBERS ON CURVES INDICATE THE TEST NUMBER (AFTER JAEGER, 1971)

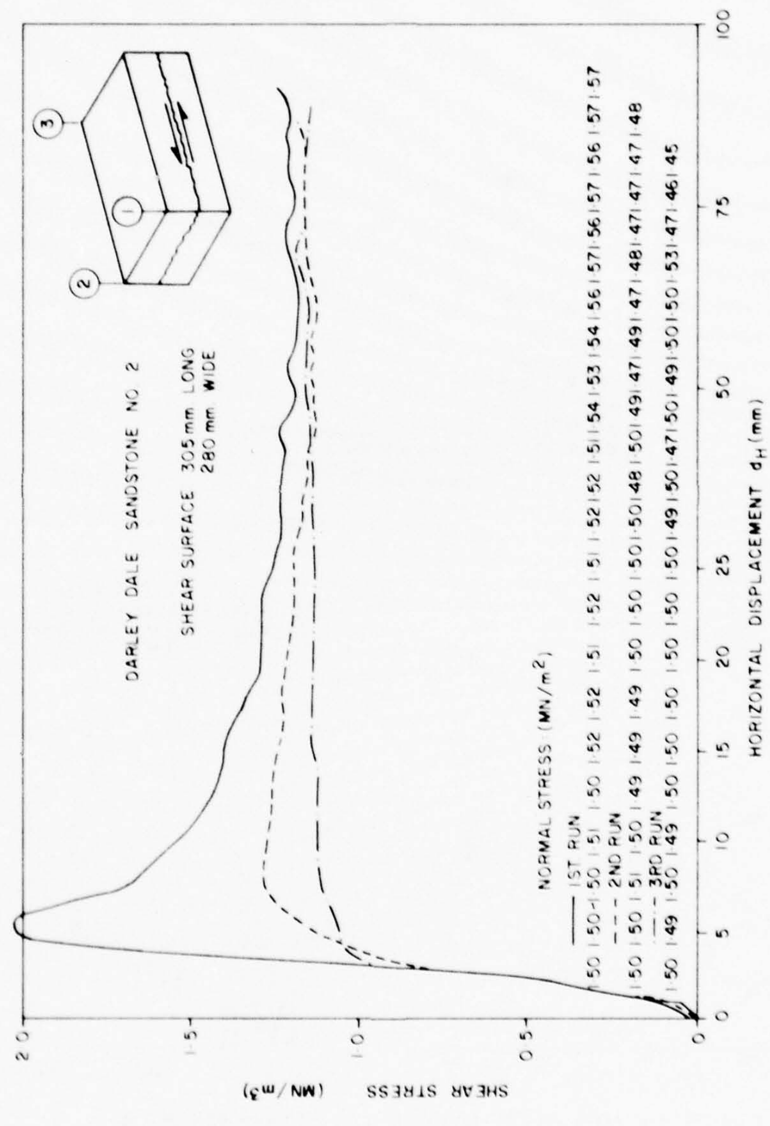


FIG. 5.10 MODIFICATION OF SHEAR STRESS-SHEAR DISPLACEMENT CURVES BY RESHEARING THE SAMPLE (AFTER KUTTER, 1974)

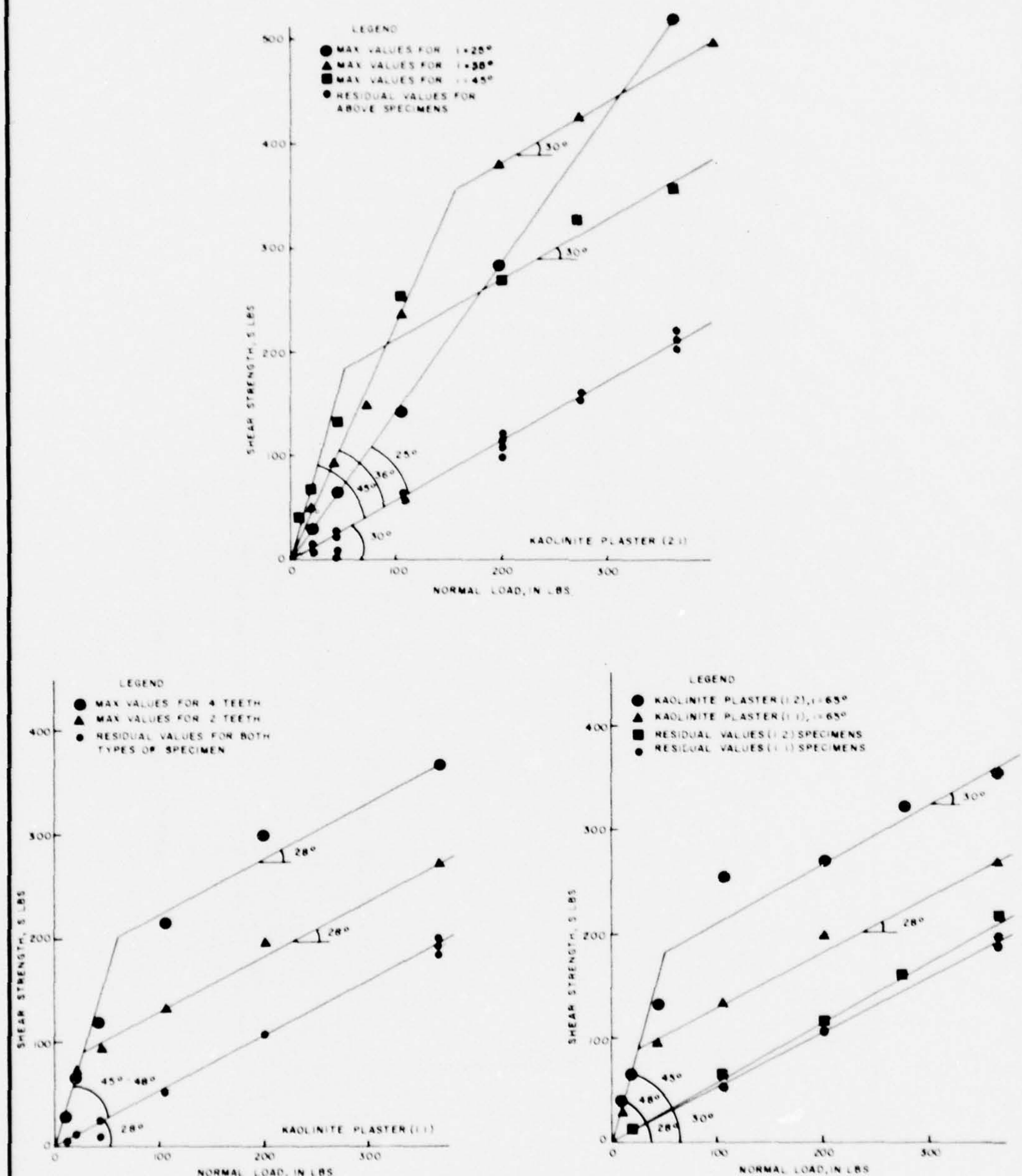


FIG. 5-11 MULTIPLE MODES OF SHEAR FAILURE IN PLASTER MODELS SHEARED ACROSS PLANES HAVING TEETH OF VARIOUS INCLINATIONS AND FREQUENCIES (AFTER PATTON, 1966)

DAMES & MOORE

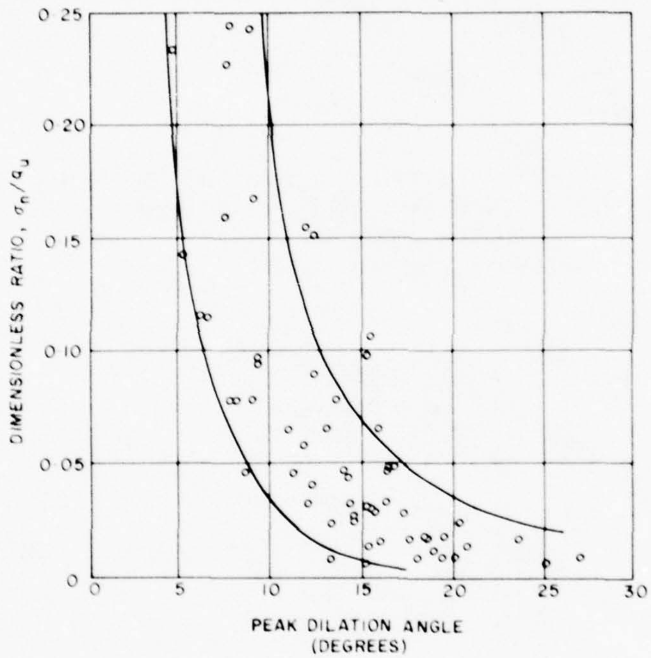


FIG. 5.12 PEAK DILATANCY ANGLE (μ) AS A FUNCTION OF THE RATIO OF NORMAL STRESS TO COMPRESSIVE STRENGTH FOR MODEL EXTENSION JOINTS (AFTER BARTON, 1971)

DAMES & MOORE

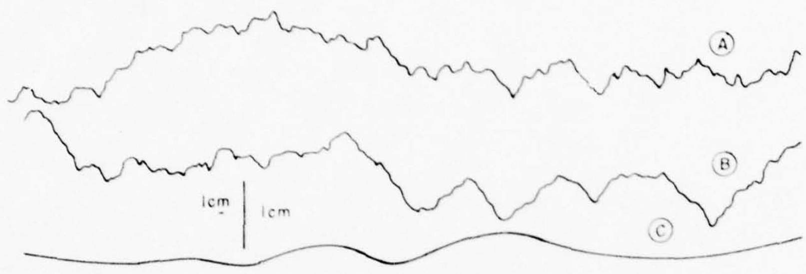


FIG. 5.13A PROFILES OF SURFACE GEOMETRIES OF JOINTS CAUSED BY TENSION IN GRANITE (A) SANDSTONE (B) AND LIMESTONE (C)
(AFTER SCHNEIDER, 1974)

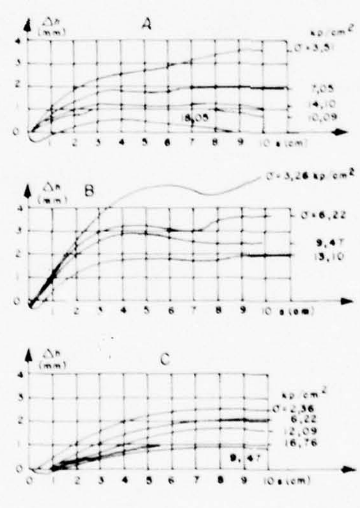


FIG. 5.13B DILATION CURVES OF THE FRICTION MODEL TESTS WITH PLASTER CASTS OF GRANITE (A) SANDSTONE (B) AND LIMESTONE (C) SURFACE GEOMETRIES
(AFTER SCHNEIDER, 1974)

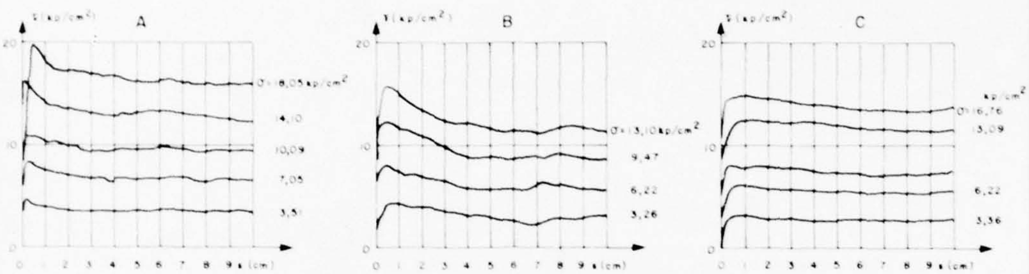


FIG. 5.13C STRESS STRAIN CURVES OF FRICTION TESTS ON MODELS WITH PLASTER CASTS OF GRANITE (A) SANDSTONE (B) AND LIMESTONE (C) JOINT FRAGMENTS (AFTER SCHNEIDER, 1974)

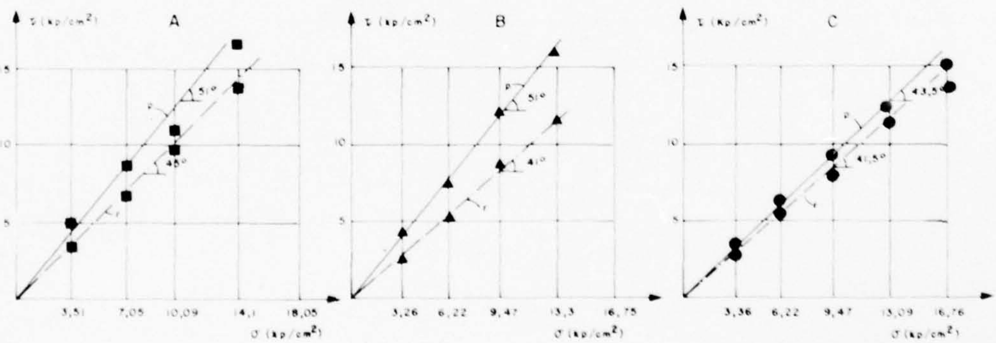


FIG. 5.13D SHEAR STRESS - NORMAL STRESS DIAGRAMS OF FRICTION TESTS ON MODELS WITH SURFACE GEOMETRIES OF GRANITE (A) SANDSTONE (B) AND LIMESTONE (C) (AFTER SCHNEIDER, 1974)

DAMES & MOORE

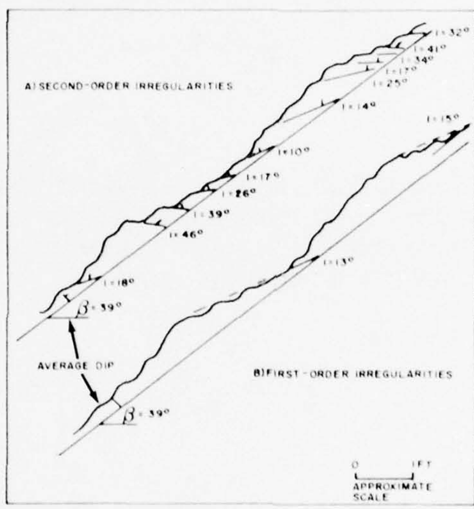


FIG. 5.14 FIRST AND SECOND ORDER IRREGULARITIES
(AFTER PATTON, 1966)

DAMES & MOORE

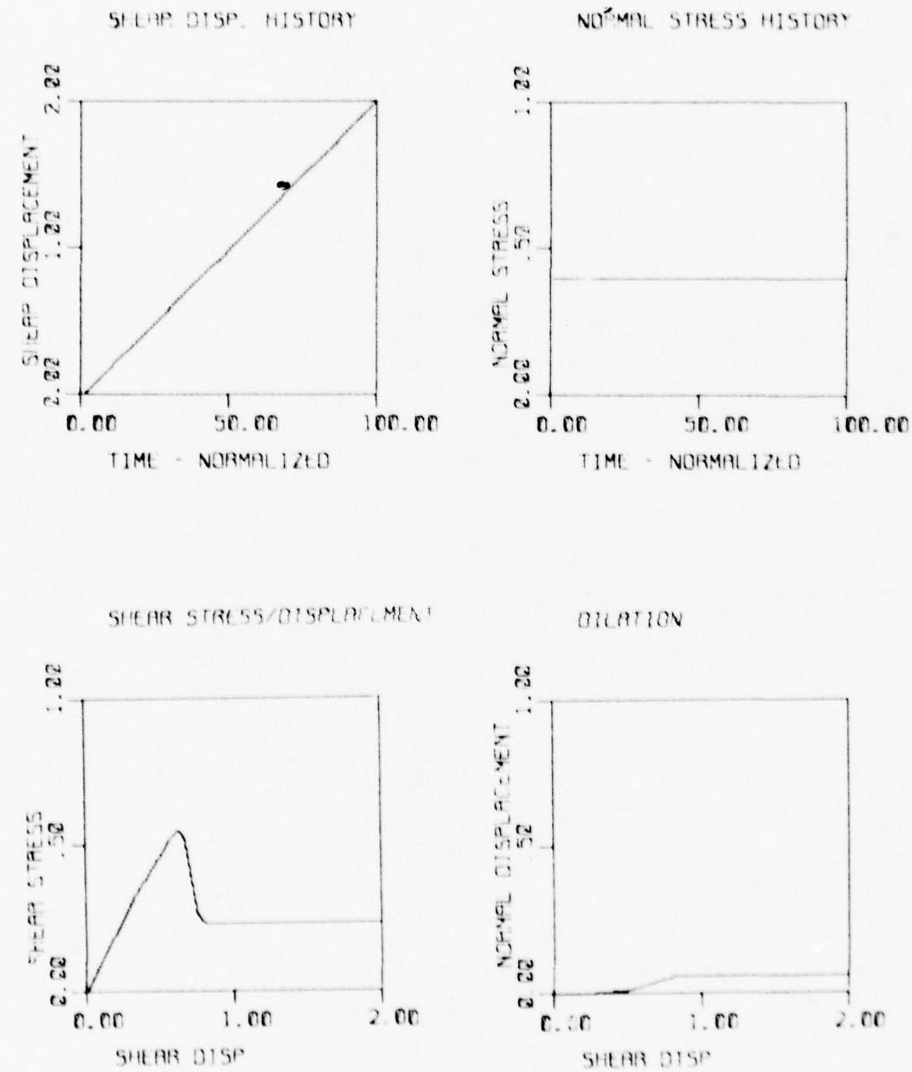


FIG. 5.15 : RUN 1 JOINT CONSTITUTIVE LAW

DAMES & MOORE

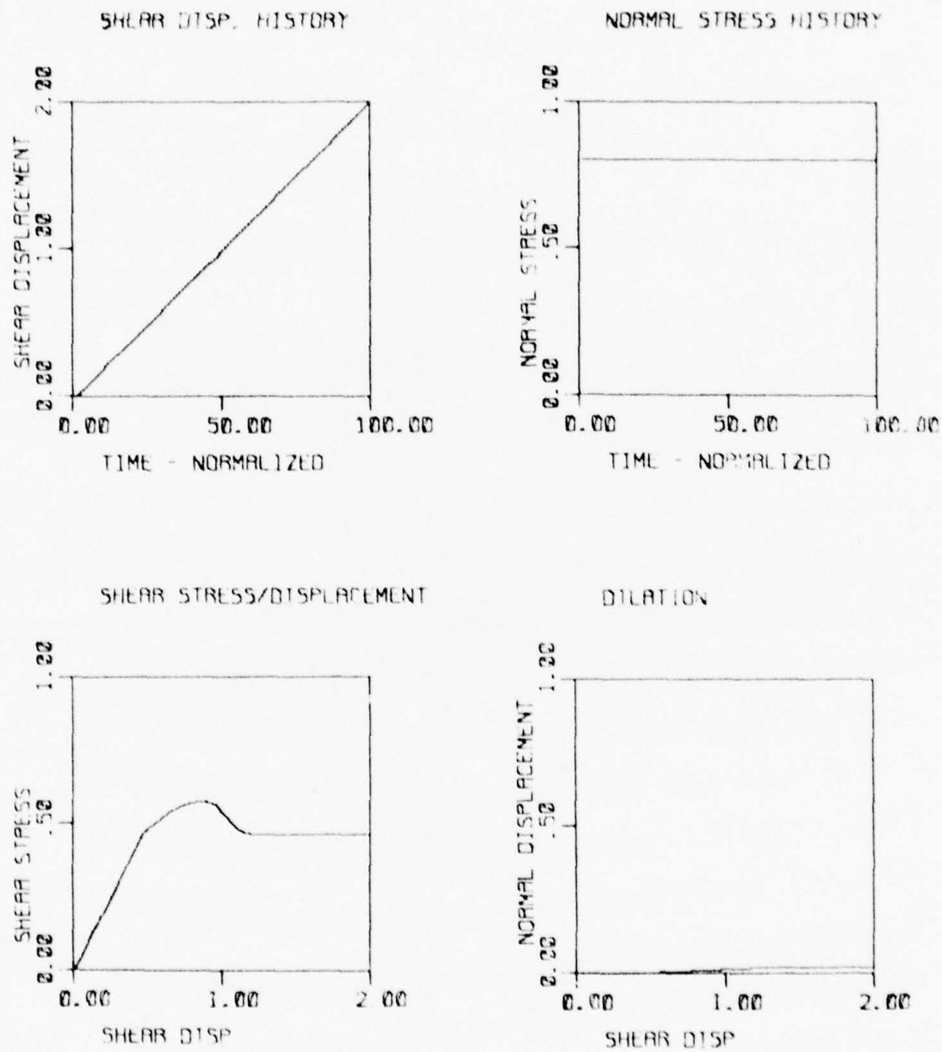


FIG. 5.16 : RUN 2 JOINT CONSTITUTIVE LAW

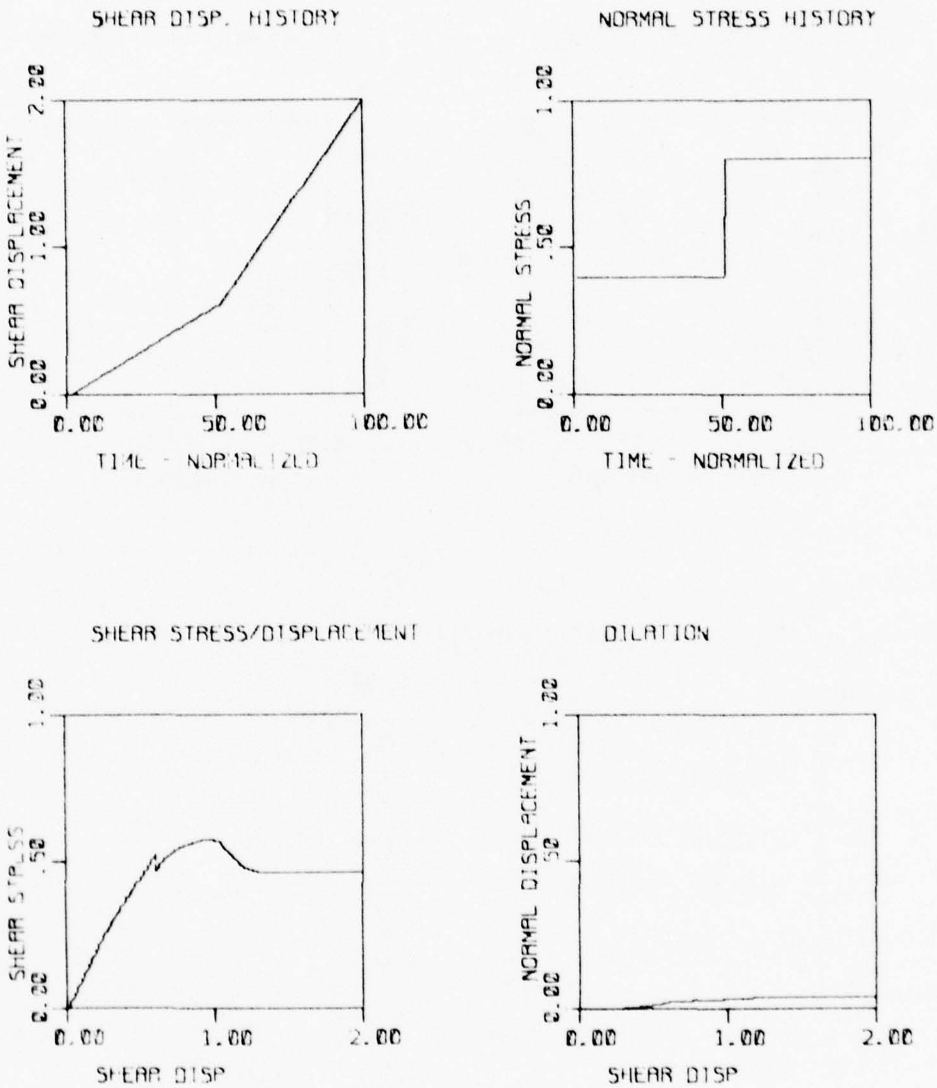


FIG. 5.17 : RUN 3 JOINT CONSTITUTIVE LAW

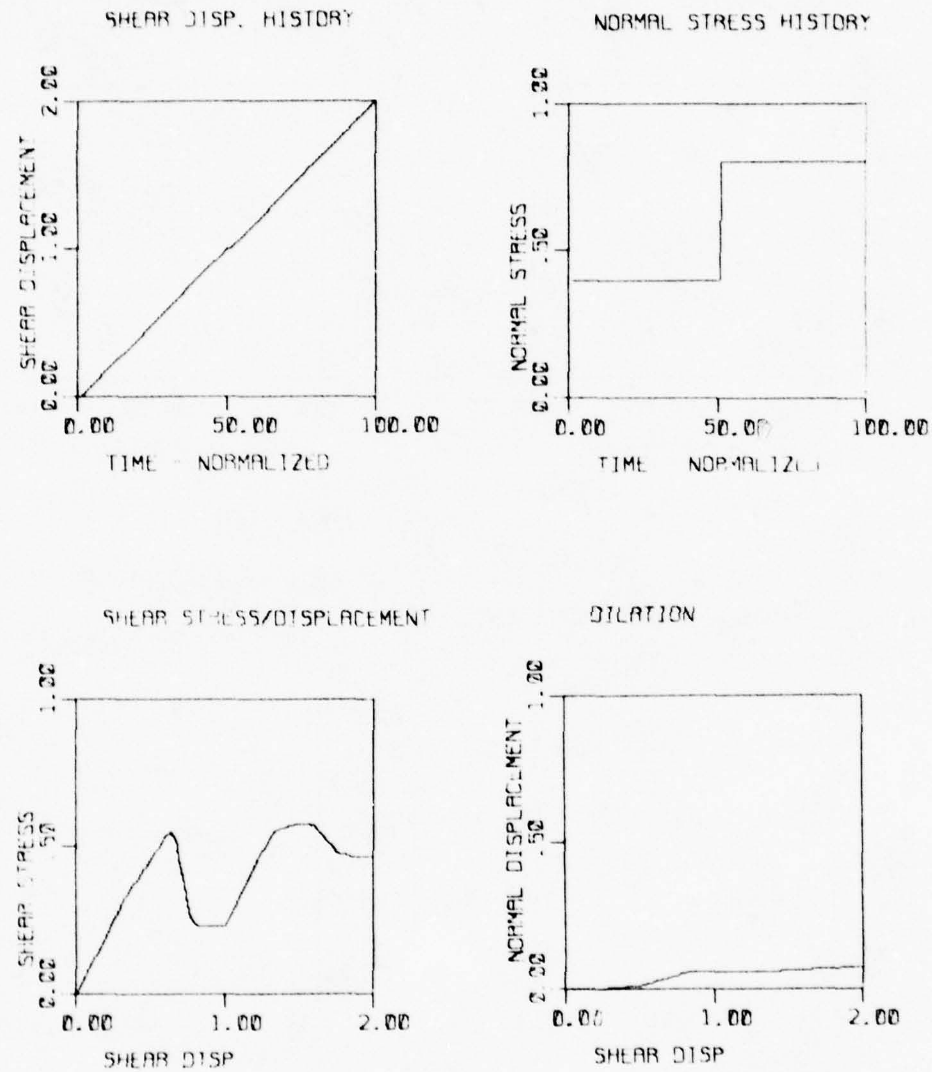


FIG. 5.18 : RUN 4 JOINT CONSTITUTIVE LAW

DAMES & MOORE

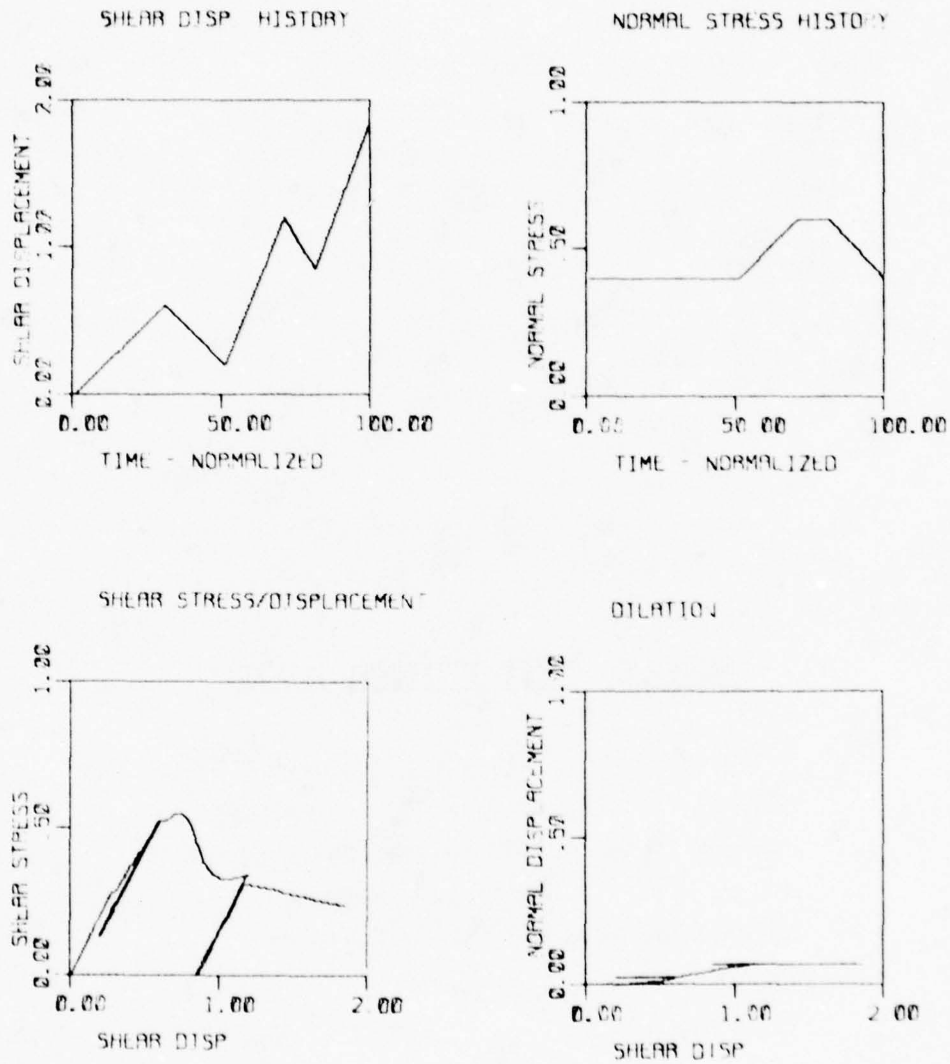


FIG. 5.19 : RUN 5 JOINT CONSTITUTIVE LAW

CHAPTER 6: FULLY-DEFORMABLE BLOCKS

6.0 *A new approach is described that could model accurately both continua as well as discontinua. The method is assessed with the aid of a simple "test-bed" program. Several examples and validations are presented.*

6.1 INTRODUCTION

6.1.1 GENERAL APPROACH

The method presented in this chapter is very general in that it can be applied to problems ranging from deformable continua to rigid or deformable discontinua. Computer programs dealing with deformable continua or rigid discontinua were already commercially available at the time of undertaking this project, but the generality of programs for analysis of fully deformable discontinua was very limited. The object of the present work was to investigate a method general enough to handle continua and discontinua as particular cases, but especially oriented to the solution of problems concerning deformable discontinua. In particular, the resulting computer program should be able to examine the interaction of arbitrary arrays of blocks with arbitrary laws governing the behaviour of the intact material and the interaction across discontinuities.

However, it must be made clear that the program described in this Chapter is not an end product. It is rather the result of a first phase of work. The purpose of this phase was the validation of the numerical approaches proposed for handling each of the problems arising in the analysis of deformable discontinua. The different assumptions are individually examined and validated in the following sections. Consequently, the program is not general in the sense that it is not provided with sophisticated input/output capabilities, and no special effort has yet been performed to optimise the data structure and the coding in order to reduce the computer time to a minimum. The program constitutes the "test-bed" for what is intended to become in the future a general user-oriented program.

The first application envisaged for the program will be the anaylsis of jointed rock masses at large depths subjected to high transient loads. By large depth it is understood here to be the depth at which the behaviour of a rock mass cannot be determined from the knowledge of its discontinuities alone. That is to say, the magnitude of the confining pressure or transient loads are so high that displacements arising from deformation of intact rock blocks are not negligible compared to those generated by rigid body movements of the blocks. This situation appears when plastification of the intact rock is likely to occur; the minimum depth required for such phenomenon is a direct function of the mechanical characteristics of the intact rock material.

6.1.2 SUMMARY OF THE METHOD

The system represented by the program is that of a set of deformable blocks. Each block is decomposed into constant-strain triangular elements and modelled as a continuum.

The continuum part of the program is a two-dimensional, finite-difference, explicit, large-deformation, Lagrangian code using triangular zones, and is based on the work of Wilkins (1969). Differences are central in time and space, and plane strain conditions are assumed. The general logic is the usual: in each time step, a) stresses are integrated about grid points to provide forces and hence accelerations, velocities and displacements; b) strains are obtained from displacements, and stresses from strains, by using the constitutive relations.

The novelty of the program lies in the treatment of contacts between blocks. When a node N from a given block contacts any other block, a new node N' is created at the contact point and the contacted triangle is decomposed into two. This procedure allows the use of practically the same treatment for contacts and continua, since in both cases a constitutive law is used to link grid-points. The only difference is that three grid-points are used for a continuum element, while two grid-points delimit a joint, with the constitutive law for the joint in between. As the node N slides on the surface of the other block, the node N' created at the contact is repositioned to follow N; in this manner, the interactive forces are always transmitted through mass points and felt as accelerations. At present the force-displacement relations for the contact are a bilinear/rigid law in the normal direction and an elastoplastic one in the tangential direction. However, these can be easily substituted in the program by any other explicit laws simply by adding a routine that embodies the desired constitutive laws. More specific details for all of the above schemes will be found in the next Sections 6.2 and 6.3.

The constitutive equations used at present for the continuum are those of an elastic material, although elastoplastic laws with strain hardening only require the addition of a few statements at the place indicated in the program.

A feature of the method described above is that both a true continuum and a true discontinuum can be accommodated as special cases. For a continuum each pair of mass-points forming a joint may be locked together rigidly, leaving the triangular zones free to deform. At the other extreme, the three mass-points of each triangle can be constrained to move together, with the joints alone being capable of deformation.

6.1.3 LAYOUT OF CHAPTER 6

Section 6.2 deals with the numerical treatment of the basic equations involved for the case of triangular zones. Mass lumping and numerical stability are also examined.

Section 6.3 is concerned with the initial discretization of the continuum and the subsequent rezoning associated with the contacts between blocks. Conservation of mass, momentum and energy for such processes is thoroughly examined.

The general organization of the program and a summarised description of each routine is provided in Appendix X and a Users' guide given in Section 6.4. Section 6.5 presents a series of examples which are intended both as checks on the program and as orientation for further use.

Conclusions and recommendations for further work are listed in Section 6.6.

The appendices VIII, IX and XVI restrict themselves to definitions of symbols and variables used, some necessary properties of triangles and a compiled listing of the program as it presently stands.

6.2 BASIC EQUATIONS AND PARAMETERS

6.2.1 CONSTITUTIVE RELATIONS

The constitutive relations are used in an incremental form, so that implementation on non-linear problems can be accomplished easily. As present, the program has been provided only with an elastic law. The place where the failure criterion should be included for treatment of elastoplastic problems with strain hardening and associated or non-associated flow rules is indicated in the listing.

The actual form of the equations used is:

$$\Delta\tau^{e}_{ij} = \lambda\ \Delta\varepsilon_{v}\delta_{ij} + 2\ \mu\Delta\varepsilon_{ij}\ (*)\,(**)$$

where λ, μ are the Lamé constants

$\Delta\tau^{e}_{ij}$ are the elastic increments of the stress tensor

$\Delta\varepsilon_{ij}$ are the incremental strains

$\Delta\varepsilon_{v} = \Delta\varepsilon_{11} + \Delta\varepsilon_{22}$ is the increment of volumetric strain

6.2.2 EQUATIONS OF MOTION

The meaning of the symbols used is illustrated in Figure 6.1.

(*) All symbols are defined in their first appearance and in Appendix VIII.

(**) i,j,k are used as indices describing tensorial character. The usual summation convention for repeated indices applies to the rest of Chapter 6.

The sum of forces at a node yields:

$$F_i^N = \int_p \tau_{ij} n_j \, ds$$

$$= \int_{p_1} \tau_{ij} n_j \, ds \text{ due to stresses being constant within zones}$$

$$= \sum_{M=1}^{N_M} \tau_{ij}^M \, \Delta s^M n_j^M$$

where F_i^N are the components of the resultant force on node N

p and p_1 are integration paths shown in Figure 6.1.

n_j are the components of the normal to the path.

s is length along the integration path.

M, ranging from 1 to N_M, covers all zones surrounding N.

In each direction:

$$F_x^N = \sum_M \tau_{xx}^M (y_2^M - y_1^M) - \sum_M \tau_{xy}^M (x_2^M - x_1^M)$$

$$F_y^N = \sum_M \tau_{xy}^M (y_2^M - y_1^M) - \sum_M \tau_{yy}^M (x_2^M - x_1^M)$$

where x,y are the coordinates and the positions of 1 and 2 in zone M as shown in Figure 6.1.

It is clear that:

$$x_2^M - x_1^M = \frac{x_N + x_E^M}{2} - \frac{x_N + x_S^M}{2}$$

$$= \frac{x_E^M - x_S^M}{2}$$

$$y_2^M - y_1^M = \frac{y_E^M - y_S^M}{2}$$

where the positions of E and S in zone M are shown in Figure 6.1.

Therefore:

$$F_x^N = \frac{1}{2} \sum_M \left[\tau_{xx}^M \; (y_E^M - y_S^M) - \tau_{xy}^M \; (x_E^M - x_S^M) \right]$$

$$F_y^N = \frac{1}{2} \sum_M \left[\tau_{xy}^M \; (y_E^M - y_S^M) - \tau_{yy}^M \; (x_E^M - x_S^M) \right]$$

Note that these formulae are independent of the order of summation through the surrounding zones, as long as all of them are included. Also, the zones need not surround completely the node considered.

6.2.3 STRAIN-DISPLACEMENT RELATIONS

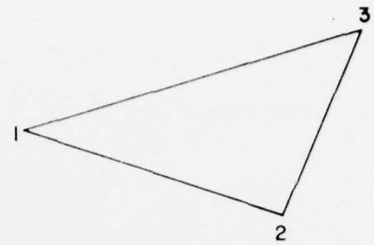
These are obtained in the following manner:

$$\dot{\varepsilon}_{xx} = \frac{\partial \dot{u}_x}{\partial x}$$

$$\dot{\varepsilon}_{yy} = \frac{\partial \dot{u}_y}{\partial y}$$

$$\dot{\varepsilon}_{xy} = \frac{1}{2}\left[\frac{\partial \dot{u}_x}{\partial y} + \frac{\partial \dot{u}_y}{\partial x}\right]$$

$$\dot{R}_{xy} = \frac{1}{2}\left[\frac{\partial \dot{u}_x}{\partial y} - \frac{\partial \dot{u}_y}{\partial x}\right]$$



where u_i is the displacement tensor

R_{ij} is the rotation tensor (positive clockwise)

dots represent time derivatives

In constant strain elements:

$$\begin{Bmatrix} \dot{u}_x \\ \\ \dot{u}_y \end{Bmatrix} = \begin{bmatrix} \dot{\varepsilon}_{xx} & \dot{\varepsilon}_{xy} + \dot{R}_{xy} \\ \\ \dot{\varepsilon}_{xy} - \dot{R}_{xy} & \dot{\varepsilon}_{yy} \end{bmatrix} \begin{Bmatrix} x \\ \\ y \end{Bmatrix} + \begin{Bmatrix} \dot{u}_{xo} \\ \\ \dot{u}_{yo} \end{Bmatrix}$$

where $\dot{u}_{xo}$, $\dot{u}_{yo}$ correspond to a rigid body movement.

Referring all coordinates and velocity components to those of node 1 in the zone:

$x_2 = x(2) - x(1)$ at time $t = (n + \frac{1}{2})\,\Delta t$, etc.

$\dot{u}_{x2} = \dot{u}_x(2) - \dot{u}_x(1)$ at time $t = n\Delta t$, etc.

Then:

$$\begin{bmatrix} \dot{u}_{x2} & \dot{u}_{x3} \\ \dot{u}_{y2} & \dot{u}_{y3} \end{bmatrix} = \begin{bmatrix} \dot{\varepsilon}_{xx} & \dot{\varepsilon}_{xy} + \dot{R}_{xy} \\ \dot{\varepsilon}_{xy} - \dot{R}_{xy} & \dot{\varepsilon}_{yy} \end{bmatrix} \begin{bmatrix} x_2 & x_3 \\ y_2 & y_3 \end{bmatrix}$$

$$\dot{\varepsilon}_{xx} = (\dot{u}_{x2} y_3 - \dot{u}_{x3} y_2) \ / \ \mathrm{DET}$$

$$\dot{\varepsilon}_{yy} = (-\dot{u}_{y2} x_3 + \dot{u}_{y3} x_2) \ / \ \mathrm{DET}$$

$$\dot{\varepsilon}_{xy} = \tfrac{1}{2}(-\dot{u}_{x2} x_3 + \dot{u}_{x3} x_2 + \dot{u}_{y2} y_3 - \dot{u}_{y3} y_2) \ / \ \mathrm{DET}$$

$$\dot{R}_{xy} = \tfrac{1}{2}(-\dot{u}_{x2} x_3 + \dot{u}_{x3} x_2 - \dot{u}_{y2} y_3 + \dot{u}_{y3} y_2) \ / \ \mathrm{DET}$$

where $\mathrm{DET} = x_2 y_3 - y_2 x_3 \neq 0$ unless 1,2,3 are aligned.

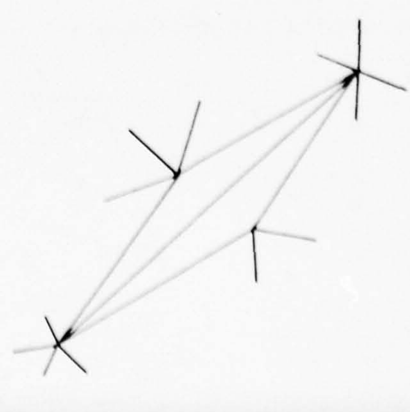
6.2.4 COMPUTATION OF THE TIME STEP

Numerical stability requires that no information be transmitted from a node to another node or edge in less than one time step. The maximum velocity of propagation is that of p-waves, which have the following velocity:

$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

where λ, μ are the Lamé constants

ρ is the mass density



The time step is computed as:

$$\Delta t = \min_{(m,n)} \left(\frac{d(mn)}{v_p(mn)} \right)$$

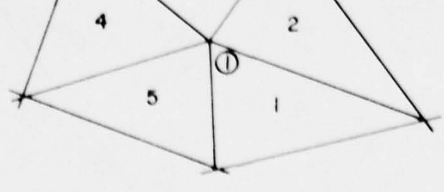
where d(mn) is the distance between two corners m and n of the same traingle and v_p(mn) is the maximum P-wave velocity possible between those two corners.

To account for situations such as the one shown in the sketch in which the minimum travel time may not occur between nodes of the same triangle, the above Δt result is multiplied by 2α (if $\alpha < 0.5$) where α is the minimum ratio of height to base for all triangles (minimum aspect ratio).

In order to guarantee stability without recomputing the time step, even after the dimensions have been altered by deformations, the result is also multiplied by FRAC, where FRAC < 1 is fixed by the user. Note that damping could also require a decrease of the FRAC value since it increases the apparent stiffness of the material.

6.2.5 MASS LUMPING PROCEDURE

As justified in Appendix IX, each grid point is assigned one third of the mass of all surrounding triangles (lower case letters will be used for grid point masses and capitals for zone masses).



MASS LUMPING SCHEME

For example, for the case shown above:

$$m_1 = \frac{M_1 + M_2 + M_3 + M_4 + M_5}{3}$$

where m_1 is the mass of node 1

M_1, M_2 ... are the masses of zones 1,2,...

6.2.6 CONSTITUTIVE LAWS ACROSS CONTACTS

Two basic types of contacts have been assumed together with their corresponding class of equations governing the interaction at the contact. Both types are examined. It is proposed that the criterion for using one type rather than the other be based on the angle between the two edges involved in the contact: if the relative angle is less than a pre-set minimum, the edge-to-edge logic would be used.

6.2.6.1 Corner-to-edge Contacts

For convenience, the normal and tangential components of the interaction will be considered independently. The tangent plane at a surface grid point is taken parallel to the line linking the two adjacent grid points.

a) Normal Direction

The normal force - normal relative displacement law postulated is shown in Figure 6.2(a).

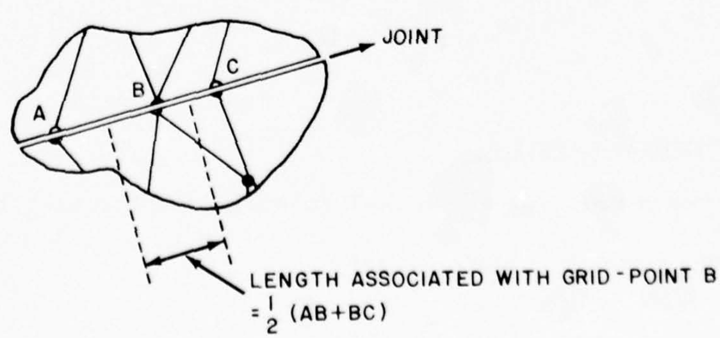
A bilinear law with no tension is assumed for relative displacements less than DN. When greater than DN, the contact is assumed rigid; i.e. the two mass-point move as one (see Section 6.2.6.3).

(b) Tangential Direction

The relationship between tangential force and relative displacement is shown in Figure 6.2(b), that is, an elastoplastic law with yield proportional to the normal component.

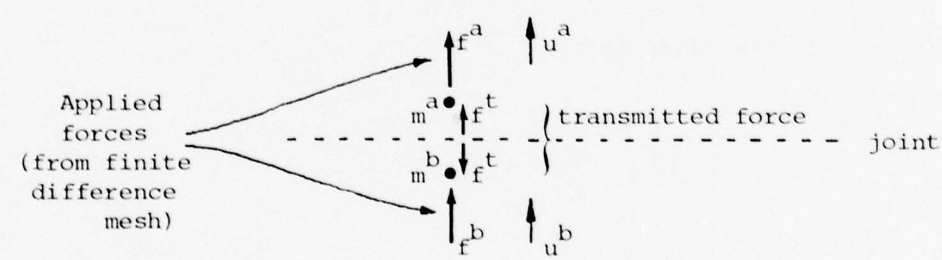
6.2.6.2 Edge-to-edge Contacts

Two edges in contact are regarded as a "joint", and the constitutive laws developed in Chapter 5 are used to derive the new normal and shear stresses from the given normal and shear displacements. Since the program needs grid-point forces, and not stresses, the stresses are multiplied by a length in order to convert them to forces. This length is assumed to be associated with the grid-point, and is taken to be the average of the distances of the grid-point from its two neighbours:



6.2.6.3 Flexible/Rigid Transition for Contacts

The normal stiffness of a rock joint characteristically increases with increased normal load. When the stiffness becomes great in comparison with that of the surrounding rock, the joint becomes "transparent" in the normal direction, and ceases to influence the mechanics of the rock mass. However, the time-step in an explicit scheme is forced to be uneconomically small by the high stiffness. For this reason program DBLOCK allows contacts to become rigid in the normal direction if the relative displacement across the joint exceeds a user-defined limit. It is still possible to evaluate the normal force between the locked grid-points, so that the calculations of slip in the shear direction can be performed as usual. The derivation of normal force is as follows:



$$m^a \ddot{u}^a = f^a + f^t$$

$$m^b \ddot{u}^b = f^b - f^t$$

If the two masses are locked together,

$$\ddot{u}^a = \ddot{u}^b$$

Hence $$\frac{f^a + f^t}{m^a} = \frac{f^b - f^t}{m^b}$$

$$\boxed{f^t = \frac{m^a f^b - m^b f^a}{m^a + m^b}}$$

This expression gives the normal force between the two opposing nodes, on the assumption that they are locked together in the normal direction. The normal force can then be utilized in the usual way by the joint constitutive law in order to derive the shear force. The transition back to flexibility in the normal direction can be determined from the magnitude of the normal force.

If a rigid/plastic law is needed for the shear direction, a similar approach may be taken in order to derive the shear force between nodes locked in the shear direction. In this case the contact is switched from the sliding state to the locked state when the relative shear velocity passes through zero. The transition in the reverse direction is determined by the magnitude of the shear force.

6.3 MESH GENERATION AND REZONING

6.3.1 AUTOMATIC MESH GENERATION

The program allows the user to supply his own mesh or to simply give the boundaries of the blocks, in which case the computer will generate automatically a triangular mesh of a given maximum edge length. This is achieved in three stages:

- The corners of the boundary are linked until the block is decomposed into triangles. The links are always established between the two closest corners. Although no holes are allowed, the number of blocks is only limited by the dimensions in COMMON and no special problems arise from locating several corners along straight or concave lines.

- The triangles are divided until all triangle edges are smaller than the length specified by the user. The edge divided is always that of maximum length in the triangle.

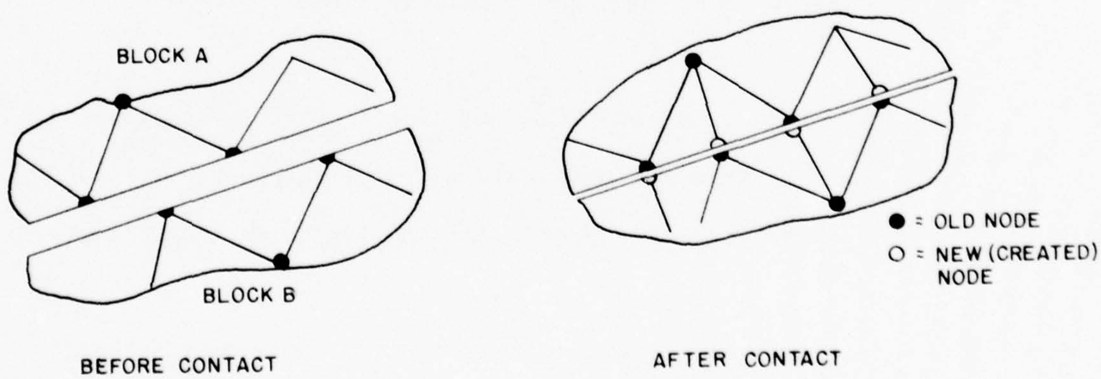
- All internal nodes are rezoned until their coordinates coincide with the average of the coordinates of the surrounding nodes. An iterative procedure is used here, since the relocation of one internal node will affect its neighbour.

In the light of the tests performed the above algorithms seem to be sufficient to provide satisfactory shapes of triangles in most instances. Note for example that it would be useless to define the block geometries with details which are small compared to the maximum triangle dimension specified by the user.

Examples of mesh generation for an odd-shaped block are given in Section 6.5.3.

6.3.2 CREATION OF A NEW NODE

When a node of a block contacts another block, a new node is created in the contacted block, in the same location as the impacting node:

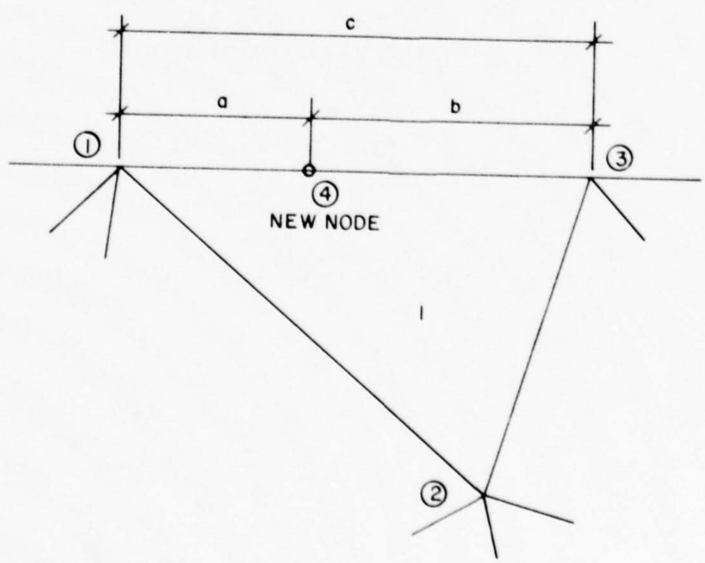


The advantage of this scheme is that it permits the natural transmission of momentum across blocks by means of forces of interaction which are felt as accelerations by the pair of nodes in contact. The creation of a new node implies a re-lumping of mass and momentum, and in

general, a change in the local energy since the momentum and energy equations cannot generally be simultaneously satisfied. In the procedures described below, mass and momentum are preserved and upper bounds in the energy increment are established proving that the errors introduced are negligible compared to other errors inherent in the discretization of the continuum.

6.3.2.1 Mass

As discussed in Appendix IX, masses are reassigned upon contact as follows (new masses indicated by an asterisk).



LET $\alpha = \frac{a}{c}$

$\beta = \frac{b}{c}$

Then:

$$m_1^\star = m_1 - \frac{M_1}{3} + \frac{M_1}{3}\,\frac{a}{c} = m_1 - \beta\,\frac{M_1}{3}$$

$$m_1^\star = m_2$$

$$m_1^\star = m_3 - \alpha\,\frac{M_1}{3}$$

$$m_4^\star = \frac{M_1}{3}$$

6.3.2.2 Momentum

In order to preserve momentum:

$$(m_1 - m_1^\star)\,\bar{v}_1 + (m_3 - m_3^\star)\,\bar{v}_3 = m_4^\star\,\bar{v}_4$$

where $\bar{v}_N$ is the vector describing the velocity of node N

$$\frac{M_1}{3}\,\beta\bar{v}_1 + \frac{M_1}{3}\,\alpha\bar{v}_3 = \frac{M_1}{3}\,\bar{v}_4$$

Hence the velocity assigned to the new node must be:

$$\bar{v}_4 = \beta\bar{v}_1 + \alpha\bar{v}_3$$

6.3.2.3 Energy

The creation of a new grid point in the form described produces a loss of kinetic energy ΔK_E:

$$\Delta K_E = \frac{M_1}{3}\beta v_1^{\,2} + \frac{M_1}{3}\alpha v_3^{\,2} - \frac{M_1}{3}\left[\beta\bar{v}_1 + \alpha\bar{v}_3\right]^2$$

$$= \frac{M_1}{3}\left[(\beta-\beta^2)v_1^{\,2} + (\alpha-\alpha^2)v_3^{\,2} - 2\alpha\beta\,\bar{v}_1\bar{v}_3\right]$$

$$= \frac{M_1}{3}\alpha\beta\left[v_1^{\,2} + v_3^{\,2} - 2\bar{v}_1\bar{v}_3\right]$$

$$= \frac{M_1}{3}\alpha\beta\,(\bar{v}_1 - \bar{v}_3)^2$$

This result shows that:

a) energy is never gained

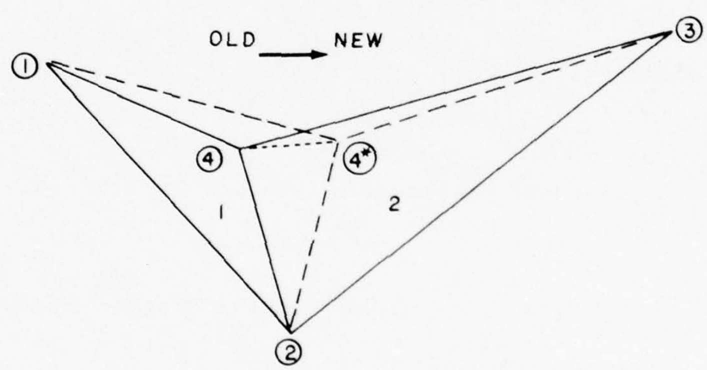
b) the energy loss goes to zero as the contact point approaches a grid point

c) the energy loss is proportional to the mass of the triangle

d) if velocities are continuous functions of the space coordinates, the energy loss goes to zero with the square of the zone size; that is, the error committed is of the same order of magnitude as the other errors associated with the discretization of the continuum.

6.3.3 "TICKLE" REZONING

Whenever the two contacting nodes separate tangentially further than TOL while maintaining normal contact, the created node is relocated. Its coordinates are made equal to those of the other node (allowing for the appropriate normal and tangential displacements corresponding to the interacting forces at that time). At present, TOL is obtained as a user-specified fraction of the distance between the two adjacent nodes.



TICKLING OF NODE 4

When the tangential distance between the two nodes in contact is less than TOL, the forces of interaction are transmitted as if the two nodes were precisely opposite each other. This introduces a moment error, which however can be made arbitrarily small as TOL is reduced.

The above sketch will be used as a guide to describe the characteristics of the tickle rezoning process.

6.3.3.1 Mass

The new zone and node masses are:

$$M_1^* = M_1 + \Delta \qquad m_1^* = m_1 + \frac{\Delta}{3}$$

$$\Delta = mass\ (424^*) \qquad m_2^* = m_2$$

$$M_2^* = M_2 - \Delta \qquad m_3^* = m_3 - \frac{\Delta}{3}$$

$$m_4^* = m_4$$

6.3.3.2 Momentum

After "tickle" rezoning nodes 1, 2 and 3 maintain their velocities. Then the conservation of linear momentum yields:

$$\frac{\Delta}{3}\bar{v}_1 - \frac{\Delta}{3}\bar{v}_3 + m_4(\bar{v}_4^* - \bar{v}_4) = 0$$

$$\bar{v}_4^* = \bar{v}_4 + \frac{\Delta}{3m_4}(\bar{v}_3 - \bar{v}_1)$$

6.3.3.3 Energy

The energy loss associated with "tickle" rezoning is:

$$2\Delta E_K = m_1v_1^2 + m_3v_3^2 + m_4v_4^2 - m_1^*v_1^{*2} - m_3^*v_3^{*2} - m_4^*v_4^{*2}$$

$$= m_1v_1^2 + m_3v_3^2 + m_4v_4^2 - (m_1 + \frac{\Delta}{3})\ v_1^2 - (m_3 - \frac{\Delta}{3})\ v_3^2$$

$$- m_4\left[\bar{v}_4 + \frac{\Delta}{3m_4}(\bar{v}_3 - \bar{v}_1)\right]^2$$

$$\frac{2\Delta E_K}{m_4} = - \frac{m}{m_4}\ v_1^2 + \frac{m}{m_4}\ v_3^2 - 2mv_4\ (\bar{v}_3 - \bar{v}_1) + m_4\left[\frac{m}{m_4}\right]^2\left[\bar{v}_3 - \bar{v}_1\right]^2$$

where $m = \frac{\Delta}{3}$

Since $\frac{m}{m_4} << 1$, $\left[\frac{m}{m_4}\right]^2$ can be neglected. Then:

$$\frac{2\Delta E_K}{m} = v_3^{\,2} - v_1^{\,2} - 2\bar{v}_4 \; (\bar{v}_3 - \bar{v}_1)$$

$$= (\bar{v}_3 - \bar{v}_1) \; (\bar{v}_3 + \bar{v}_1) - 2\bar{v}_4 \; (\bar{v}_3 - \bar{v}_1)$$

$$= (\bar{v}_3 - \bar{v}_1) \; (\bar{v}_3 + \bar{v}_1 - 2\bar{v}_4)$$

$$\Delta E_K = m \; (\bar{v}_3 - \bar{v}_1) \left[\frac{\bar{v}_1 + \bar{v}_3}{2} - \bar{v}_4\right]$$

which means that:

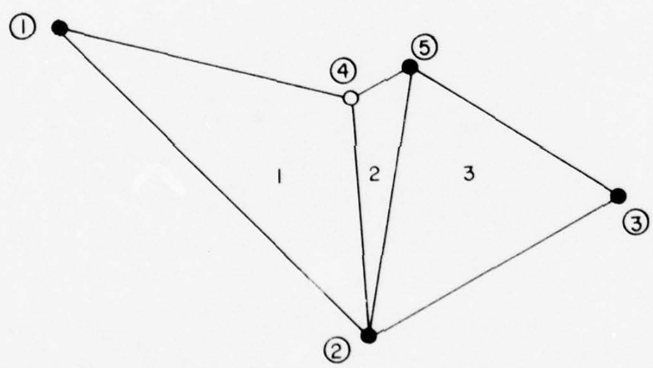
1) the energy loss is never negative (m changes sign with the dot product).

2) the energy loss is proportional to the mass transferred and goes to zero when the two outer corners (1,4) have equal velocities, or when their average is equal or perpendicular to the velocity of the created node (4).

3) as the mesh becomes smaller, the energy loss approaches zero as the product of the transferred mass times the square of the zone dimension.

6.3.4 DELETION OF TRIANGLES

Due to the tickle-rezoning accompanying sliding, one of the nodes created at a contact may approach another pre-existing node. When the zone common to those two nodes becomes too small, that zone is deleted. Following the nomenclature in the sketch below, zone 2 and node 4 will disappear when node 4 approaches node 5.



DELETION OF NODE 4

In this sketch, nodes 1, 4 and 5 are boundary nodes; 4 was created at a contact with another block.

The criterion used by the program to decide whether to delete a node or not is based on the aspect ratio of the diminishing triangle; specifically, the triangle is deleted when its aspect ratio becomes smaller than that needed to guarantee stability for the time increment used.

6.3.4.1 Mass

The zone masses become:

$$M_3^{\star} = M_3$$

$$M_1^{\star} = M_1 + M_2$$

And the node masses:

$$m_1^{\star} = m_1 + m_o$$

$$m_2^{\star} = m_2$$

$$m_3^{\star} = m_3$$

$$m_5^{\star} = m_4 + m_5 - m_o$$

where $m_o = \dfrac{M_2}{3}$

6.3.4.2 Momentum

All but node 5 preserve their previous velocities. Then, conservation of momentum implies:

$$m_1\bar{v}_1 + m_2\bar{v}_2 + m_3\bar{v}_3 + m_4\bar{v}_4 + m_5\bar{v}_5 = m_1^{\star}\bar{v}_1^{\star} + m_2^{\star}\bar{v}_2^{\star} + m_3^{\star}\bar{v}_3^{\star} + m_5^{\star}\bar{v}_5^{\star}$$

$$m_1\bar{v}_1 + m_4\bar{v}_4 + m_5\bar{v}_5 = (m_1 + m_o)\ \bar{v}_1 + (m_4 + m_5 - m_o)\ \bar{v}_5^{\star}$$

and hence:

$$\bar{v}_5^* = \frac{m_4\bar{v}_4 + m_5\bar{v}_5 - m_o\bar{v}_1}{m_4 + m_5 - m_o}$$

6.3.4.3 Energy

The loss in kinetic energy associated with this rezoning is:

$$2\Delta E_K = m_1 v_1^2 + m_2 v_2^2 + m_3 v_3^2 + m_4 v_4^2 + m_5 v_5^2 - m_1 v_1^{*2} - m_2 v_2^{*2} - m_3 v_3^{*2} - m_4 v_4^{*2}$$

$$= m_o v_1^2 + m_4 v_4^2 + m_5 v_5^2 - (m_4 + m_5 - m_o) \left[\frac{m_4\bar{v}_4 + m_5\bar{v}_5 - m_o\bar{v}_1}{m_4 + m_5 - m_o} \right]^2$$

By simple reorganization of terms, this can be expressed as:

$$2\Delta E_K = \frac{m_4 m_5 (\bar{v}_4 - \bar{v}_5)^2}{m_4 + m_5 - m_o} - m_o \cdot \frac{m_4 (\bar{v}_4 - \bar{v}_1)^2 + m_5 (\bar{v}_5 - \bar{v}_1)^2}{m_4 + m_5 - m_o}$$

Assuming that velocities are continuous functions of the coordinates:

$$\Delta E_K = O(d^2) - O(d)O(e^2)$$

where d = distance from 4 to 5

e = zone typical dimension

O (˙) = ' of the order of'

Note that the first term represents an energy loss and the second represents a gain. Also that the errors associated with a constant strain triangular configuration are of the order of e^2. Since d is small compared to e, the error introduced by the rezoning described is negligible compared to that inherent in the method of discretization of the continuum.

6.3.5 OTHER DETAILS

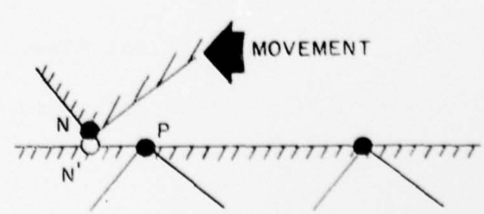
The main procedures for creation of the mesh and its rezoning have been described in earlier sections. To complete the description, some minor details should also be mentioned.

6.3.5.1 Recreation of Contact Nodes

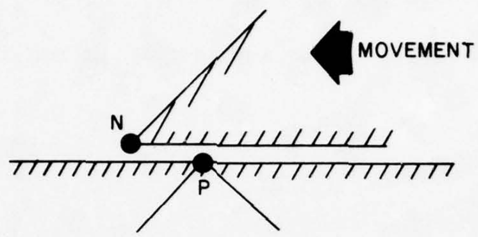
It has been shown before how a node created at a contact is "tickled" to follow its partner; also, how the former is deleted when, due to successive "tickling" one of the triangles about the "tickled" node becomes very slender.

Consistent with those procedures, once the impacting node N goes past a certain distance from the opposite (non tickleable) node P, a new node N' is created to continue opposing N'.

The distance N'P minimum for the re-creation of the node is taken 50% greater than the distance for deletion of the node. This hysteresis avoids continuous creation and deletion of the same node.



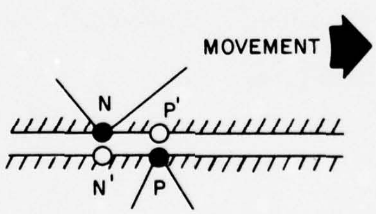
The same formulation given in Section 6.3.2 for the creation of a new node applies for the re-creation. Note that two nodes are re-created at the same time



unless two contacts (N to P and P to N) already exist (see Section 6.3.5.2). Clearly, once N goes past P, nodes opposing both N and P will need re-creation.

6.3.5.2 Redundant Contacts

The deletion of nodes in the case of two adjacent contacts must be handled with special care.



From the above sketch it is clear that nodes P' and N' will soon be deleted. From the deletion of P', a contact P to N will appear; from deletion of N', another contact N to P will appear. If nothing is done, the same contact will be taken into account twice per time step. This is not considered realistic and, besides, it is likely to create problems of stability.

6.4 USE OF PROGRAM DBLOCK

As remarked earlier, the program is not intended as a "user-oriented" package, but is simply a test-bed for proving the numerical scheme. In consequence the input and output is rudimentary.

6.4.1 FILES

No file numbers are referred to in the program since simple PRINT and READ statements are used for output and input. The format for the input stream is given in Appendix X.

6.4.2 PRINTED OUTPUT

The computer provides an echo of all input data as well as the values of all velocities, coordinates and stresses at the iteration cycle numbers requested by the user. However, this type of output is lengthy and difficult to visualise.

6.4.3 PLOTTED OUTPUT

The output is much more manageable in the form of plots. The computer can provide two different types of plots:

6.4.3.1 Meshes

A plot of the complete finite difference mesh will be plotted at the required scale at the cycle numbers pre-selected by the user. The number of plots is at present restricted to 10 by the dimensions in COMMON but can be increased as desired within the core capabilities of the computer used.

6.4.3.2 Histories

The program is prepared to provide time histories of two variables. The two variables of which the history is requested are specified in the routine OUTPUT by statements of the form:

```
BUF1 (NPL) = YD(6)
BUF3 (NPL) = XD(6)
```

The two variables desired should replace XD(6) and YD(6) in the two statements mentioned. The program will then create a file for plotting which can then be plotted by a post-processor.

This is in contrast with the mesh plots which are controlled directly by the program.

6.4.4 BOUNDARY CONDITIONS

The boundary conditions must be inserted explicitly as FORTRAN statements in the routine BOUNDY. This routine is simply:

```
SUBROUTINE BOUNDY
INCLUDE 'COMMON.FTN'
..........
..........
RETURN
END
```

If node 3 is to be fixed in the X-direction, then the user will replace the dots in the above listing by:

```
XD(3) = 0
```

Similarly for any other boundary conditions.

6.4.5 DAMPING

Only stiffness-proportional damping is provided, and is similar to that embodied in program RBM (see Section 2.4.6).

6.5 EXAMPLES AND VALIDATIONS

In this section several examples are presented. Their purpose is two fold: on the one hand, they provide a verification of the adequacy of the program while, on the other hand, they provide a clarification of the type of results generated by the program as well as of its capabilities.

6.5.1 STATIC TESTS UNDER UNIFORM CONDITIONS

The mesh used for these tests was taken to be very irregular with the purpose of verifying the accuracy of the results under difficult conditions. The mesh is shown on Figure 6.3.

Several tests were performed with this mesh. Figure 6.4 shows the theoretical and numerical results when the mesh is subjected to gravity.

It was also verified that all nodes reached equilibrium and stresses were uniform when the domain considered was subjected to uniform boundary stresses.

Another static test performed consisted of imposing a relative vertical displacement between the two horizontal boundaries. In one case, the nodes on the vertical boundaries were forced to the positions they should reach under deformation; in the second case, they were allowed vertical freedom to attain such positions naturally. The results are compared with the true solution in the following tables:

Constrained Case

	Theoretical	Numerical
τ_{xx}	3.75	3.7707
τ_{yy}	1.25	1.2569
τ_{xy}	0	$\leq 6.7\times10^{-6}$

Unconstrained Case

	Theoretical	Numerical
τ_{xx}	3.7500	3.7707
τ_{yy}	1.2500	1.2569
τ_{xy}	0	$\leq 9.8 \times 10^{-6}$

6.5.2 WAVE PROPAGATION TESTS

The theoretical velocity of propagation of different waves was compared to that observed from the results of the program. For this purpose, a twenty-story bar was generated and subjected to gravity in different positions and under different boundary conditions. In this way, three types of waves were generated: a) P-waves in a constrained material, b) P-waves in material constrained in one transversal direction but free in the other, and c) S-waves.

A comparison of the accuracy of the resulting periods of oscillation is provided in the next table.

		THEORETICAL VALUE (sec)	OBSERVED VALUE (sec)
P-WAVE	FULLY CONSTRAINED	3.88	3.89
	SEMI-CONSTRAINED	7.12	7.00
S-WAVE		13.66	13.68

The reason why the semi-constrained case does not appear to be as accurate as the others is that the theoretical propagation assumes no lateral inertia in the unconstrained direction. Such inertia, though small, does exist in the numerical representation, thus slightly biasing the result towards the fully constrained value (infinite lateral inertia).

An example of the velocity history is also presented in Figure 6.5. It corresponds to the case of the propagation of the shear wave. Note that the theoretical history is composed of straight lines.

6.5.3 MESH GENERATION TESTS

Several tests were made to illustrate the capabilities of the mesh generating process. Figure 6.6 presents the information initially given to the computer, namely, twelve boundary nodes. Figure 6.7 presents the mesh at the end of the triangularization by MESH. Figures 6.8A and 6.9A show the mesh as obtained by REDUCE for the cases of maximum edge sizes of 3.0 and 2.4 cm, respectively. Finally, Figures 6.8B and 6.9B depict the meshes corresponding to the two cases mentioned after the rezoning carried out by NICE.

6.5.4 BLOCK SLIDING ON INCLINED PLANE

The interest of this test, besides that of providing a clear display of the rezoning activities of the program, is to check the conservation of momentum and energy throughout the rezoning procedure.

The initial configuration is displayed in frame A of Figure 6.10. A three zone block is pushed downslope with vertical and horizontal velocities equal to -1.0. Gravity exists and is equal to 0.98 (units are arbitrary). Under those conditions the vertical velocity of the block should be:

$$v_y = 1 - 0.49t$$

The subsequent frames (6.10B to 6.10I) illustrate the rezoning process. The plot in Figures 6.11 shows a comparison of the theoretical velocity with that computed for the back node of the sliding block. As can be seen, the agreement is very satisfactory and no appreciable energy or momentum losses have been accumulated in the process. Figure 6.12 presents a plot in which the block is pushed without gravity. As shown, no energy is spent in the rezoning procedures.

For the runs described above, the following properties were used:

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COMPUTER MODELING OF JOINTED ROCK MASSES.(U)
AUG 78 T MAINI, P CUNDALL, J MARTI DACA39-77-C-0004
UNCLASSIFIED WES-TR-N-78-4 NL

3 OF 6
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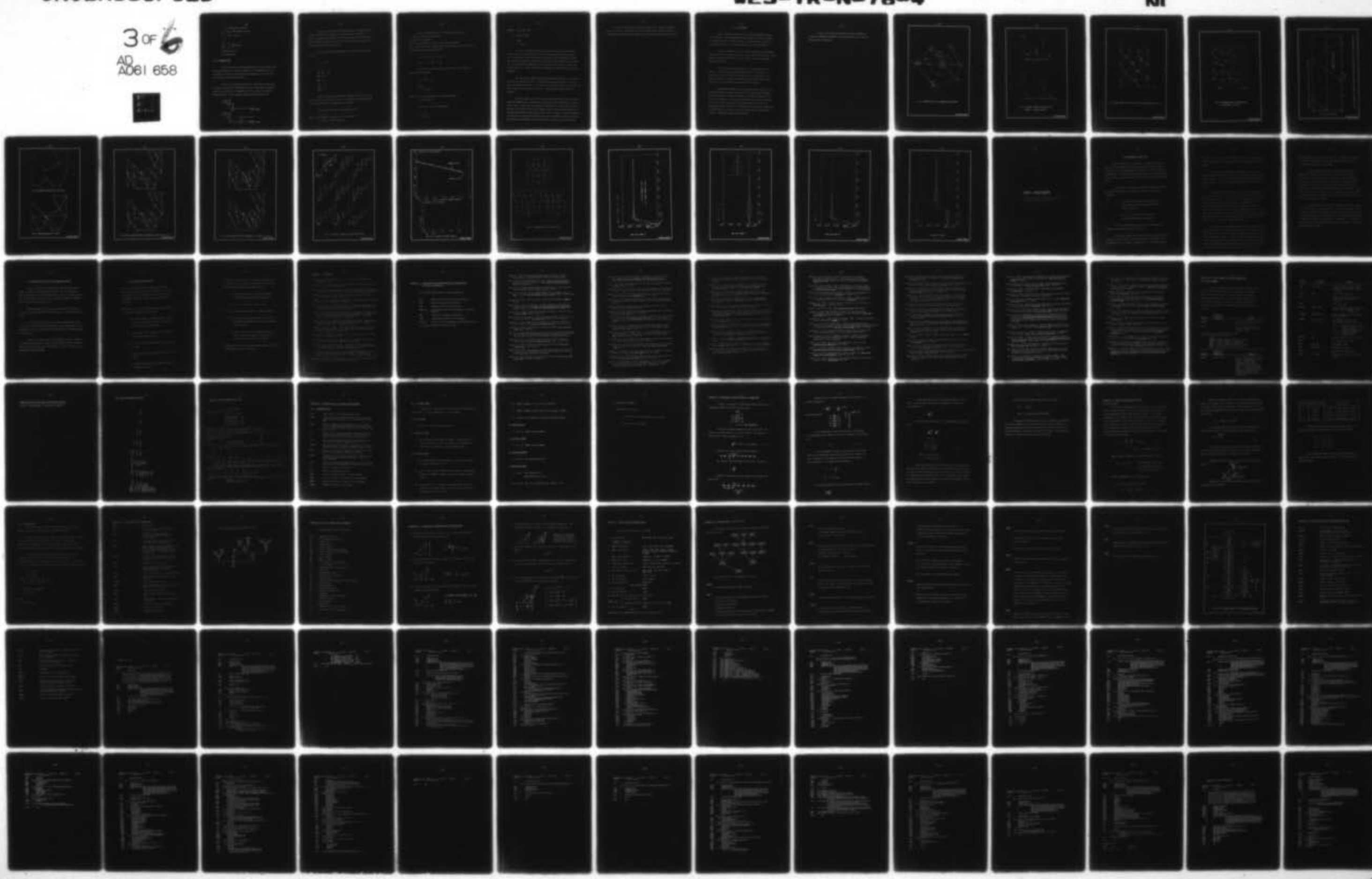
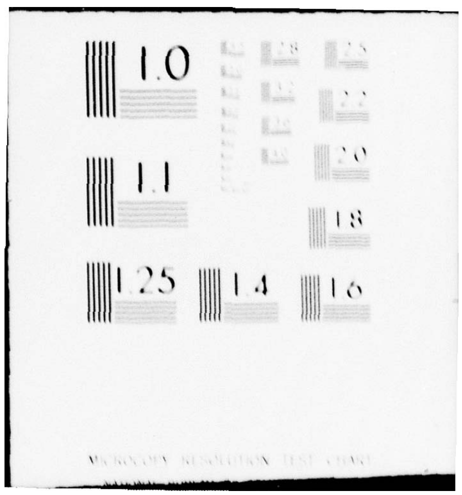



1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
MICROCOPY RESOLUTION TEST CHART

$\lambda = \mu = 1000$ (Lame's constants)

$K_{NL} = K_{NU} = 5000$ normal stiffness

$\delta_n =$ rigid transition

$\rho = 1$

$$\left.\begin{array}{l} \lambda_{min} = 5\% \\ f_{min} = 10.0 \end{array}\right\} \text{damping}$$

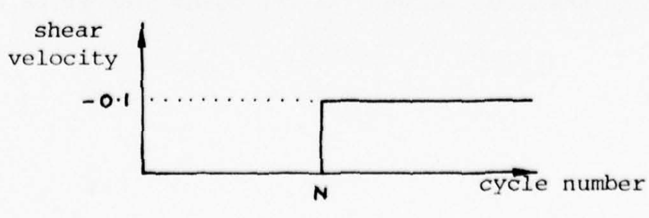
slope angle = 45°

g = 0.98 gravity

6.5.5 SHEARBOX TEST

Similar tests to be those performed with the block sliding downslope were undertaken to study the behaviour of a simulated shear test configuration. Figure 6.13A presents the arrangement of two blocks and their initial finite difference grids.

As seen in the referenced figure, all five nodes in the lowest horizontal plane remain fixed during the tests. The boundary conditions, specified as velocities, are applied on the five nodes in the highest horizontal plane. Those boundary conditions were as shown below:



Clearly, the two blocks are first compressed together; when this situation stabilizes, the upper plane of the top block is forced to displace horizontally with respect to the lower plane of the bottom block. Total resultant horizontal and vertical forces along the top horizontal plane were monitored during the test.

Material properties and parameters used in these tests were as follows:

$\lambda = \mu = 1000$

$\rho = 1$

$g = 0$

$K_{NL} = K_{NU} = 5000$

$K_{SH} = 1000$

$XMU = 0.1$

$\lambda_{min} = 0.7$

$f_{min} = 2.0$

$FRAC = 0.5$

Figures 6.14 to 6.17 present the results of the tests together with the theoretical static results. It is probably worth mentioning how the theoretical result for compression was obtained.

The total relative vertical displacement d is:

$d = d_1 + d_2$

where d_1 corresponds to compression of the continuum

d_2 occurs at the discontinuity.

Since the resultant force F is equal across any section:

$F = n\, K_{NL}\, d_2$ across the discontinuity

$F = K_1 d_1$ in the continuum

where n is the number of contacts across the discontinuity.

K_1 is similar to a Young's modulus under plane-strain conditions and can be obtained from the following relations:

$$\tau_{xx} = \lambda\ (\varepsilon_{xx} + \varepsilon_{YY}) + 2\mu\ \varepsilon_{xx} = 0$$

$$\tau_{YY} = \lambda\ (\varepsilon_{xx} + \varepsilon_{YY}) + 2\mu\ \varepsilon_{YY}$$

Eliminating ε_{xx} between both equations, and for the values of the parameters proposed,

$$\tau_{YY} = 2666.7\ \varepsilon_{YY}$$

Hence:

$$F = 2666.7\ \frac{A}{H}\ d_1$$

Where A is the cross-sectional area (assumed constant)

H is the height

In terms of the total displacement:

$$F = \frac{d}{\frac{1}{K_1} + \frac{1}{K_2}}$$

Where $K_1 = 2666.7 \frac{A}{H} = 2666.7$

$K_2 = n\, K_{NL} = 35000$

Hence:

$F = 135.72$

It can be seen that the dynamic solutions converge to the theoretical static ones. Figures 6.14 and 6.15 present the normal and shear forces during Test A, in which the shear displacement started after 1000 iterations (N = 1000). The initial oscillations of the shear force coupled to the compression are thought to be originated by the asymmetry of the mesh and decay due to the stiffness damping incorporated. A small but similar coupling effect is observed at the onset of shearing.

The same test was repeated with shearing velocity equal to -0.05 starting after only 300 iterations (Test B). Normal and shear forces for this test are presented in Figures 6.16 and 6.17. The shear force seems to converge to a slightly low value compared to the theoretical solution. Apart from that the results are as expected.

A special feature of the two tests described was that the nodes of the top and bottom boundaries were allowed free relative horizontal displacement until the onset of shear. Other tests (not presented) showed that a slightly larger value is obtained for the normal load if these boundary nodes are horizontally fixed, due to the obvious constraints on the Poisson's ratio effect. However, as could be expected, such horizontal constraints decreased the effect of the unwanted coupled oscillations introduced by mesh asymmetry and the shear forces converged to the correct value.

Finally, a test was also run without normal force, simply by providing an initial velocity. The constant velocity observed proves again that energy is conserved during rezoning; such rezoning can be visualised in Figures 6.13A to 6.13C.

6.6 CONCLUSIONS

A basic program has been written to analyse deformable continua and discontinua. The program, DBLOCK, works explicitly in the time domain by a Lagrangian finite difference scheme. The implementation of arbitrary constitutive relations for continuous materials is relatively simple.

The contacts between blocks are handled by special logic depending on whether they are considered corner-to-edge or edge-to-edge contacts. Again, arbitrary laws governing the interaction at those contacts are straightforward to introduce.

The main novelty of the program lies on the handling of the contacts. Two grid points are permanently opposed in each contact, the contact forces, hence, being felt by those nodes as accelerations. The meshes are rezoned as required to maintain the two nodes in each contact opposing each other throughout the duration of the contact.

The hypotheses embodied in the program have been tested on static and dynamic problems against analytical solutions, with special emphasis on the conservation of energy and momentum. The results obtained to date are very encouraging. For quasi-static problems, where velocity gradients are low, the errors associated with rezoning tend to zero, since the equations presented in Section 6.3 show that the energy error is proportional to the difference in velocity of the nodes either side of the node being relocated. Momentum is always conserved exactly.

Finally, the program has been provided with a method for generating automatically meshes of the desired densities to cover the domains under consideration.

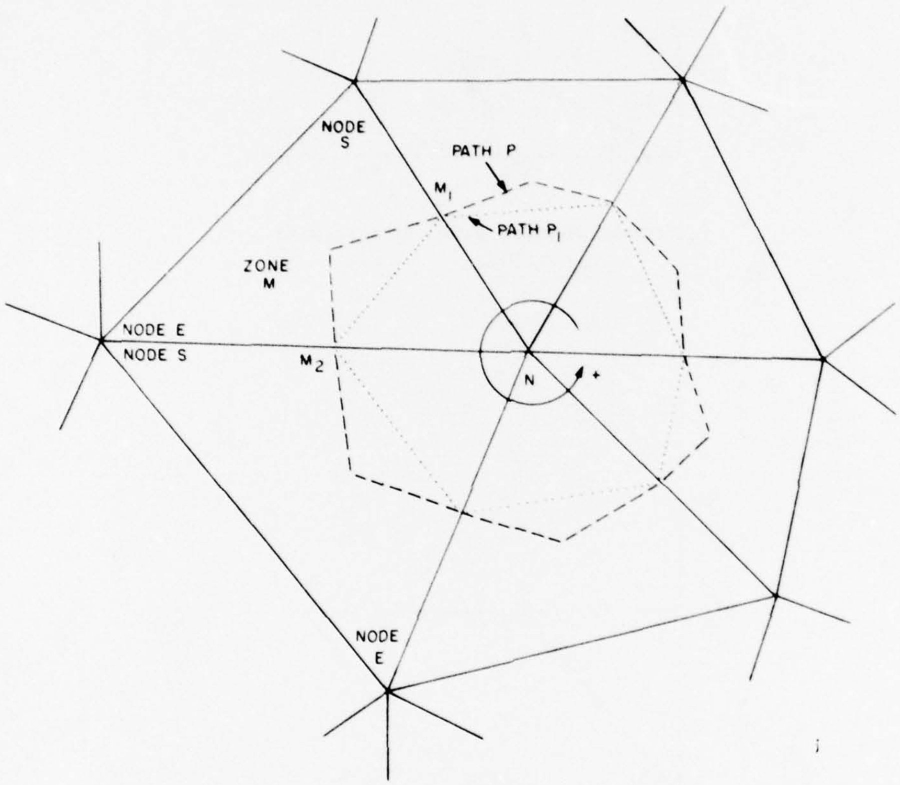
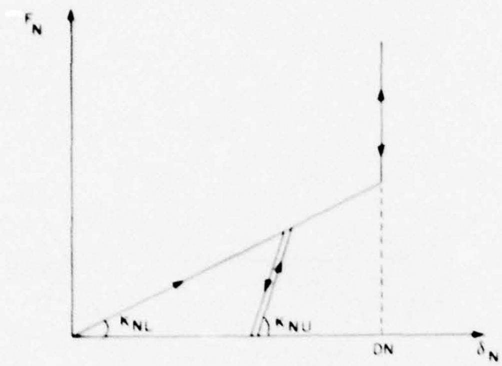
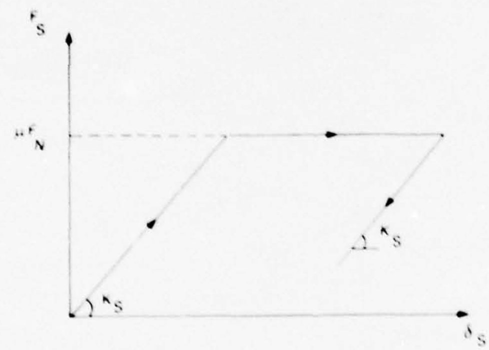


FIG. 6.1 INTEGRATION OF THE MOMENTUM EQUATIONS

DAMES & MOORE



(a) NORMAL FORCE vs NORMAL DISPLACEMENT



(b) TANGENTIAL FORCE vs TANGENTIAL DISPLACEMENT

FIG. 6.2 ASSUMED CONSTITUTIVE LAWS FOR CORNER - TO EDGE CONTACT

DAMES & MOORE

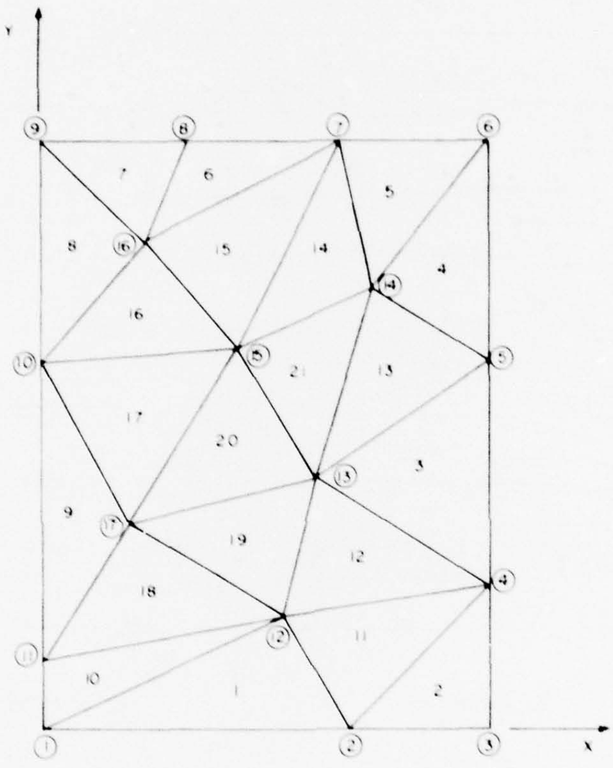


FIG. 6.3 MESH USED FOR THE STATIC TESTS ON PROGRAM D BLOCK

DAMES & MOORE

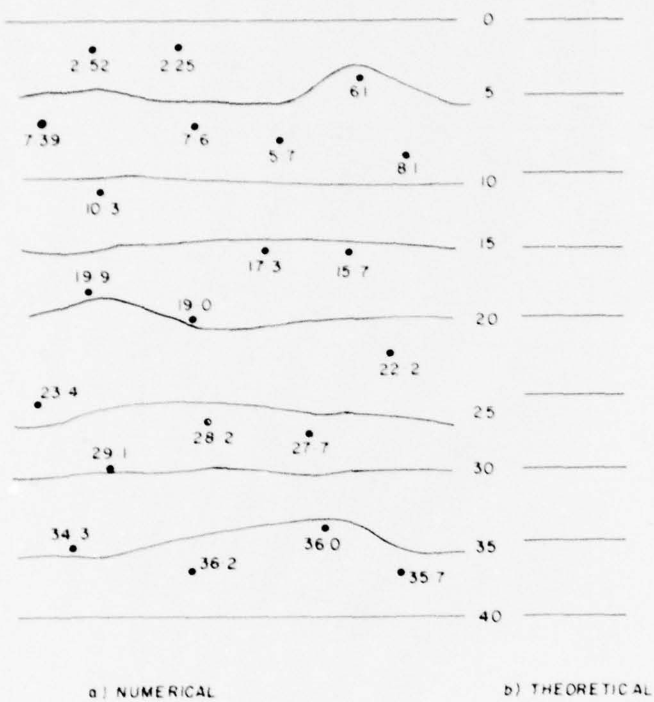


FIG. 6.4 STRESSES DUE TO GRAVITATION ON THE MESH OF FIG. 6.3

DAMES & MOORE

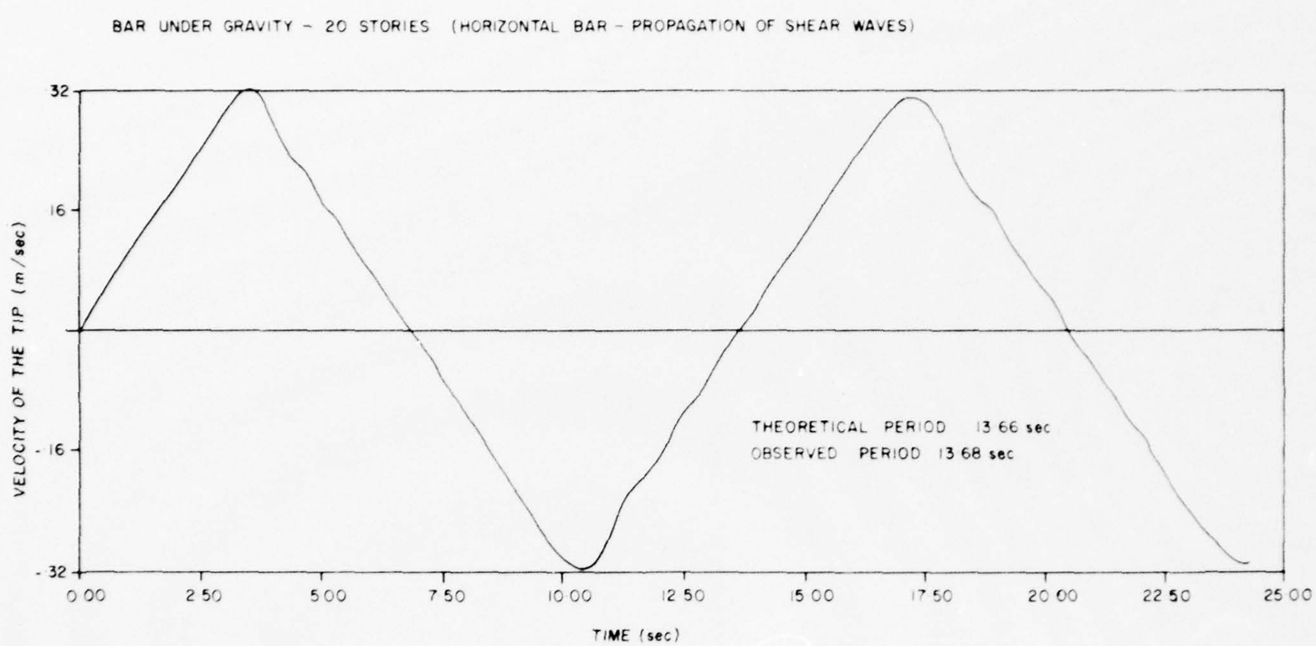


FIG. 6.5 EXAMPLE OF VELOCITY HISTORY IN WAVE PROPAGATION TEST OF PROGRAM DBLOCK

DAMES & MOORE

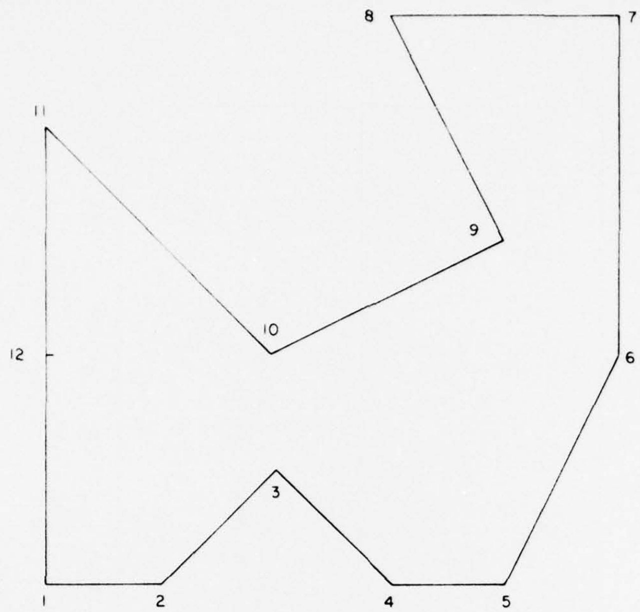


FIG.6.6 BOUNDARY SUPPLIED BY THE USER

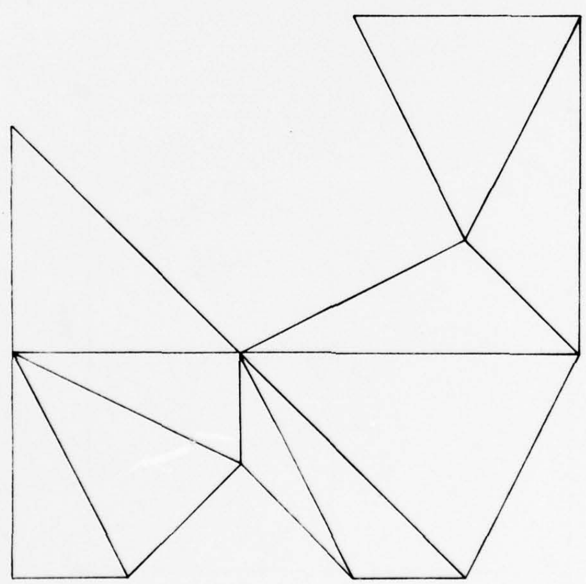
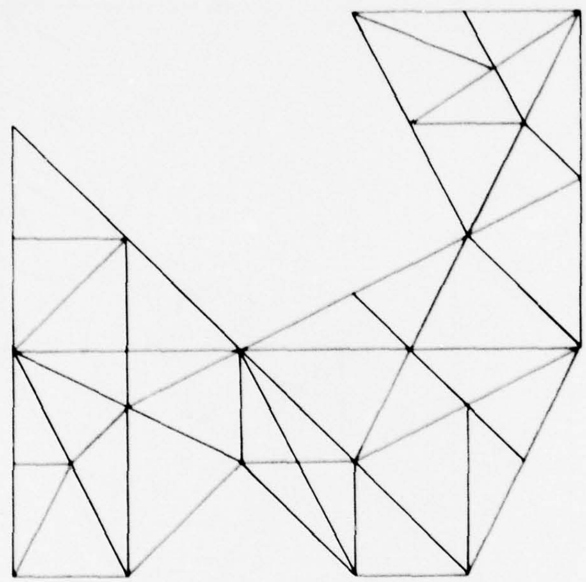
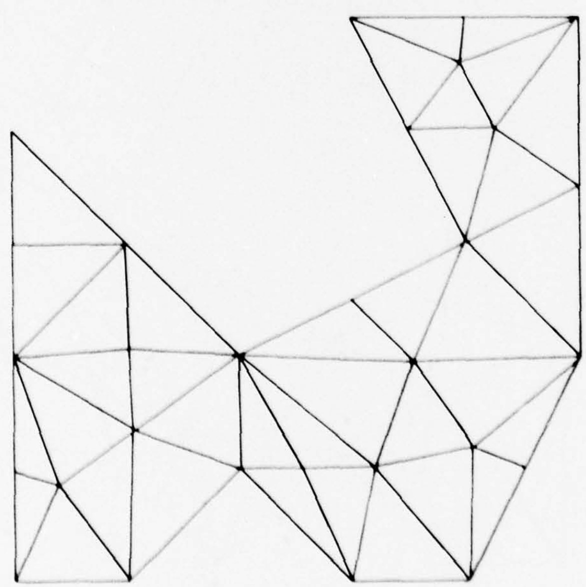


FIG.6.7 TRIANGULARIZATION BY 'MESH'



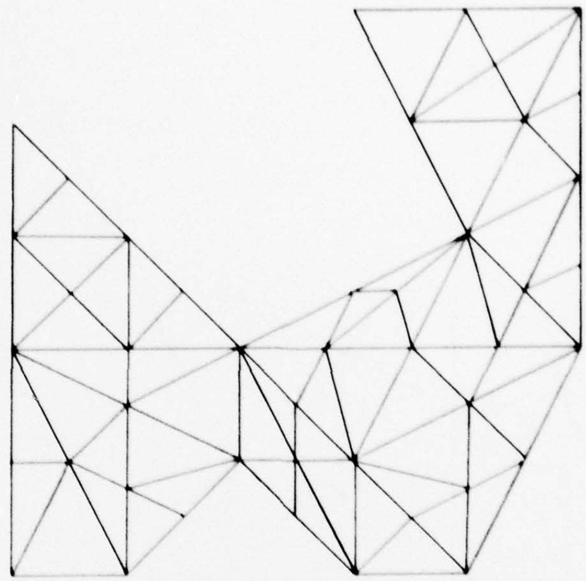
A) MESH AT THE END OF 'REDUCE'



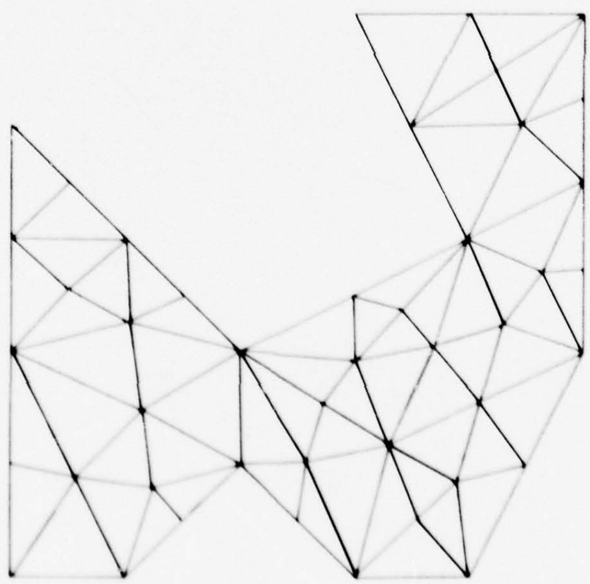
B) MESH AT THE END OF 'NICE'

FIG. 6.8 MESH GENERATED WITH A MAXIMUM EDGE LENGTH OF 3.0 CM

DAMES & MOORE



A) MESH AT THE END OF 'REDUCE'



B) MESH AT THE END OF 'NICE'

FIG. 6.9 MESH GENERATED WITH A MAXIMUM EDGE LENGTH OF 2.4 CM

DAMES & MOORE

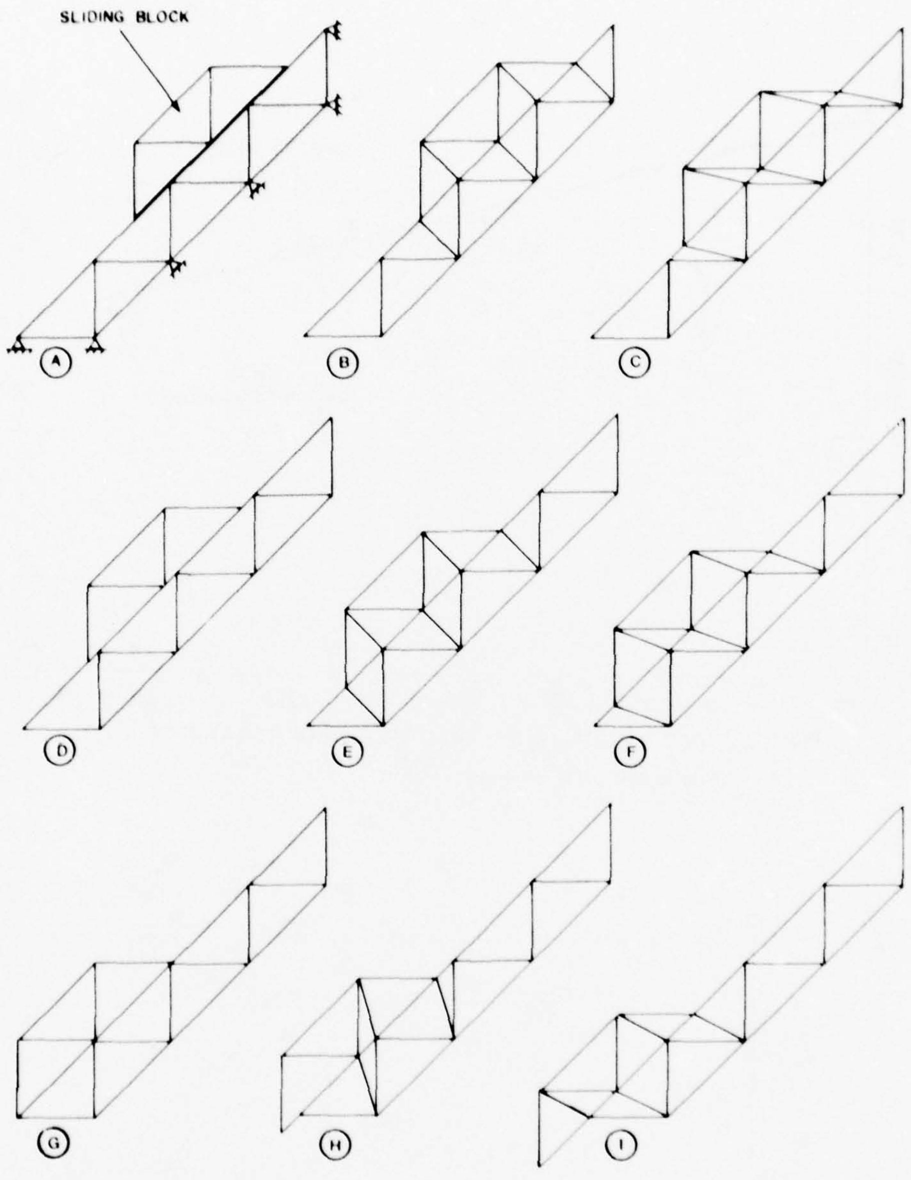


FIG. 6.10 BLOCK SLIDING ON AN INCLINED PLANE

DAMES & MOORE

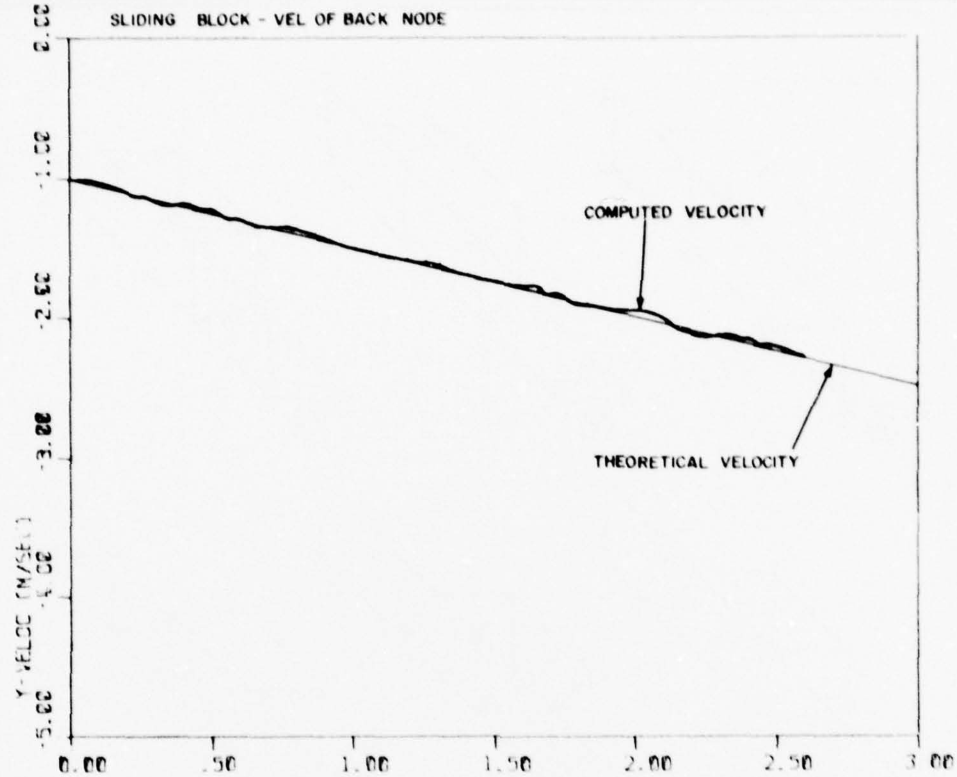


FIG. 6.11 VELOCITY UNDER GRAVITY

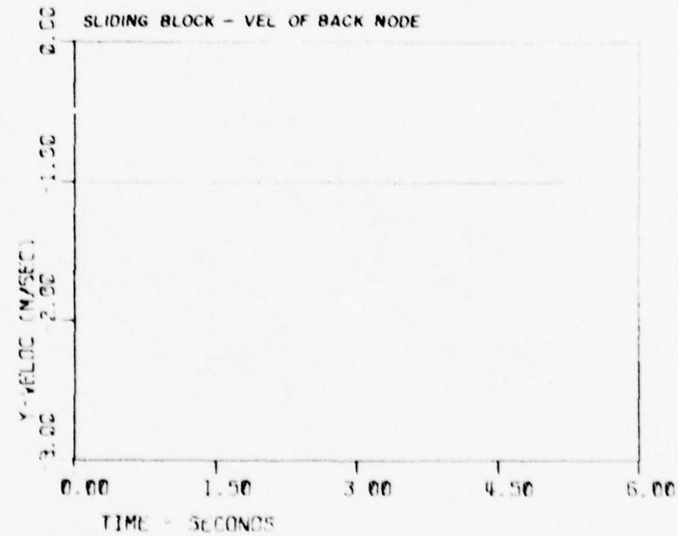


FIG. 6.12 VELOCITY WITHOUT GRAVITY

DAMES & MOORE

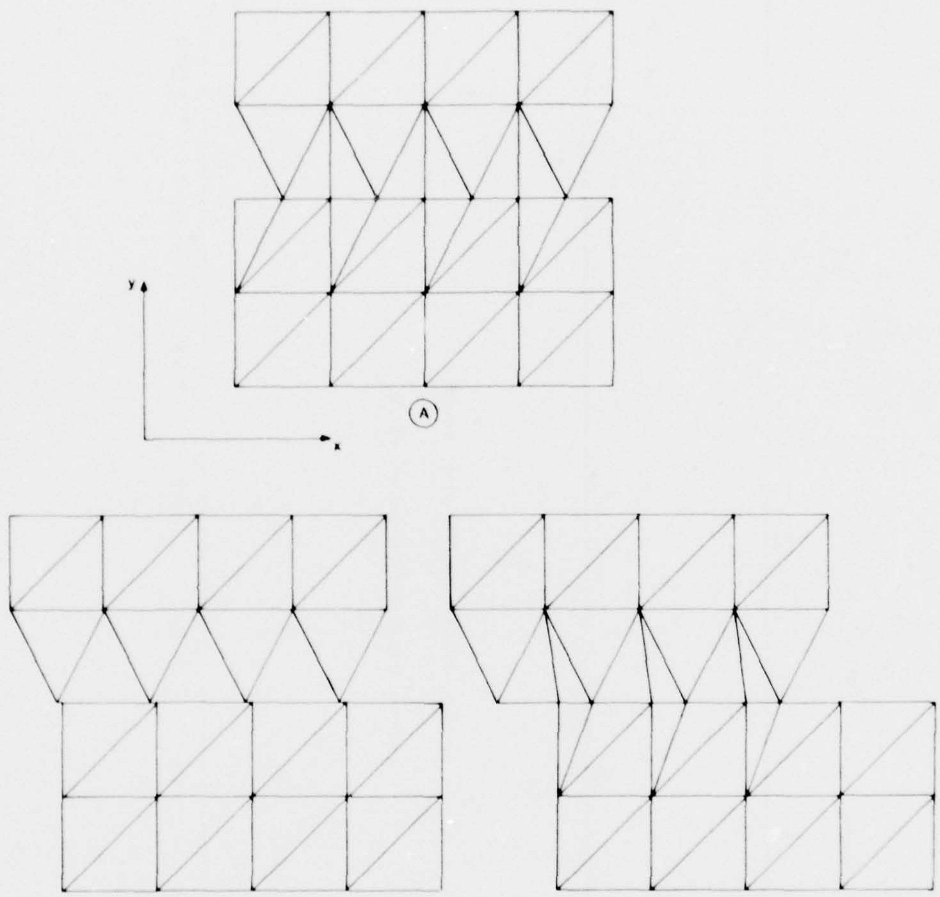


FIG. 6.13 SHEAR-BOX TEST - MESH PLOTS

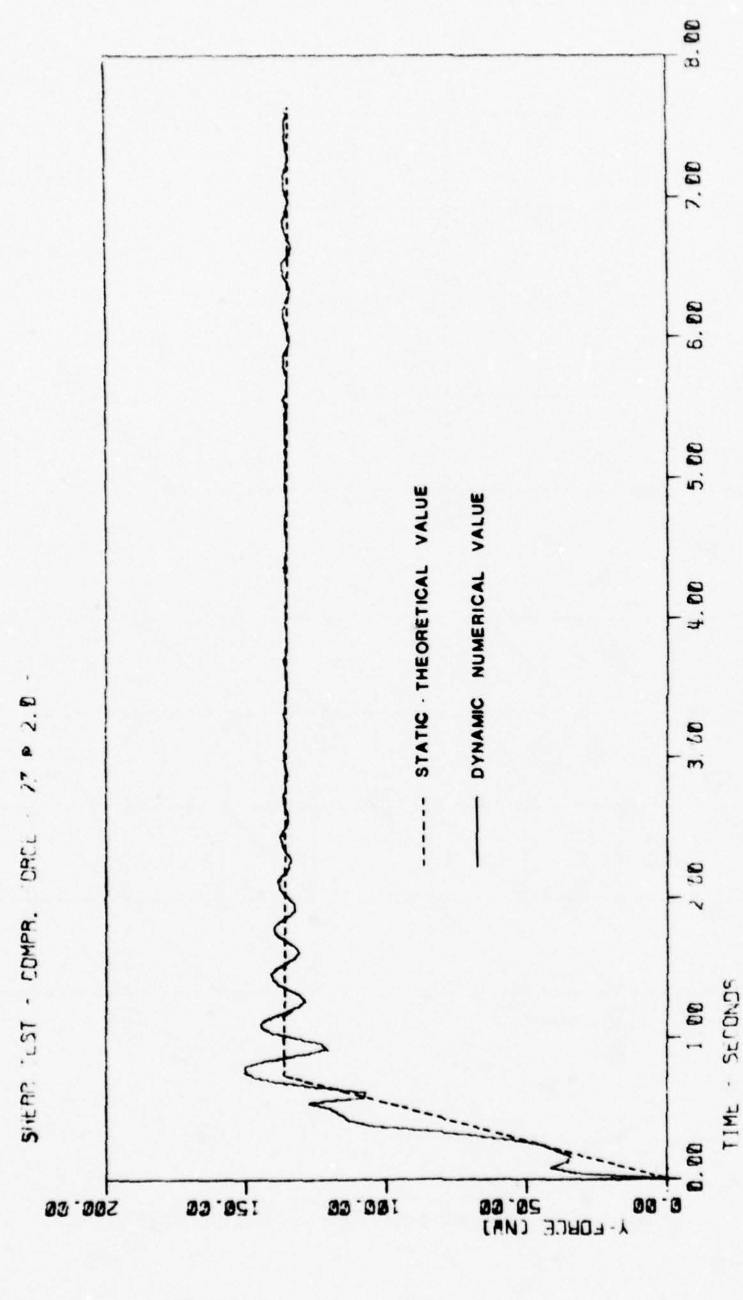


FIG. 6.14 TEST A

DAMES & MOORE

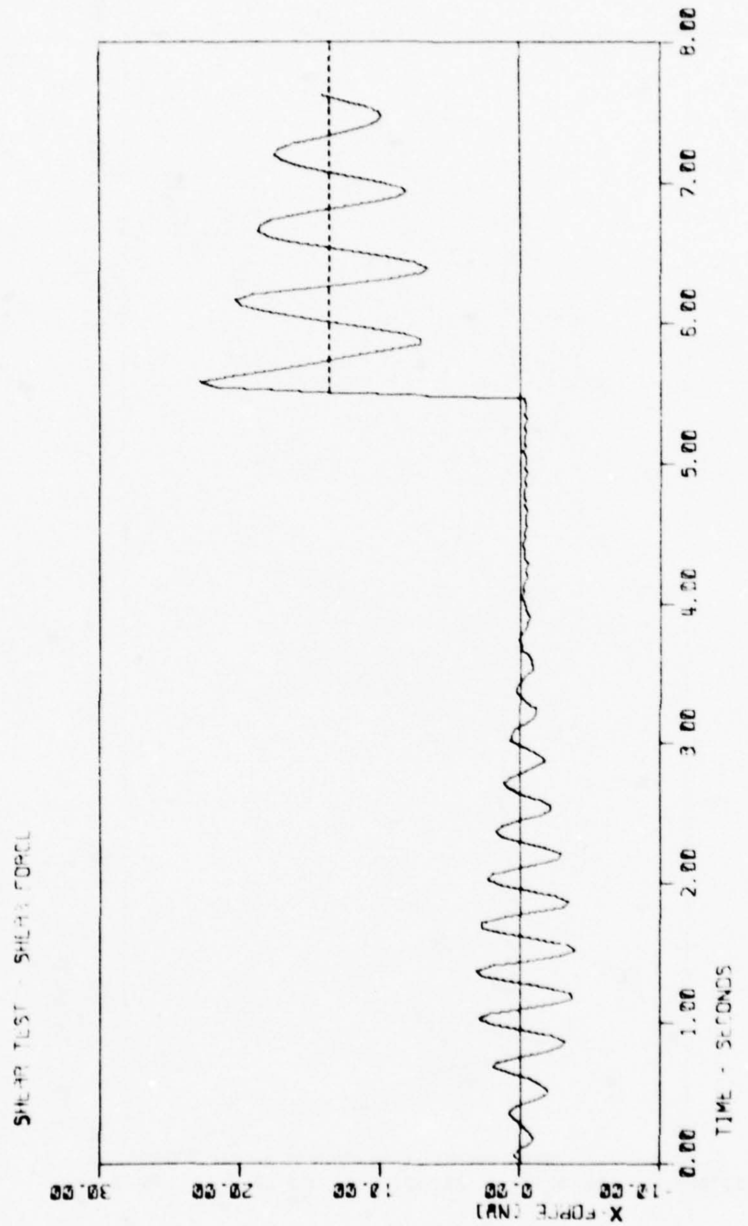


FIG. 6.15 TEST A

DAMES & MOORE

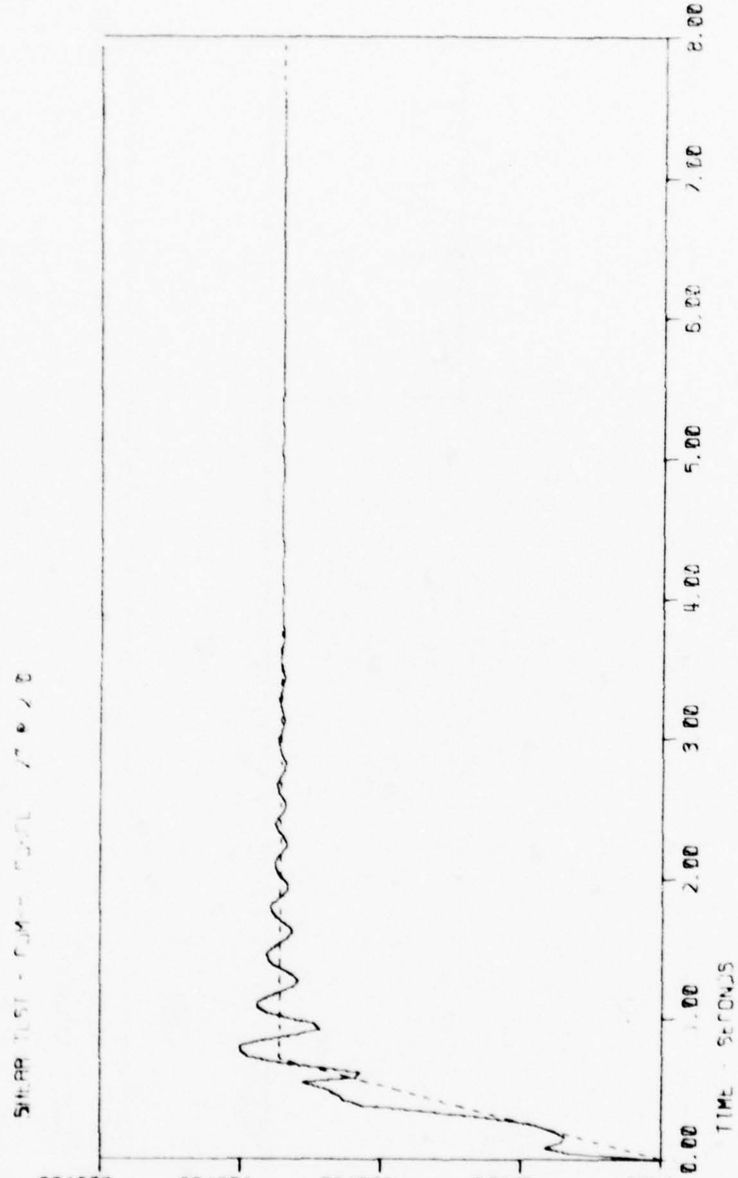


FIG. 6.16 TEST B

DAMES & MOORE

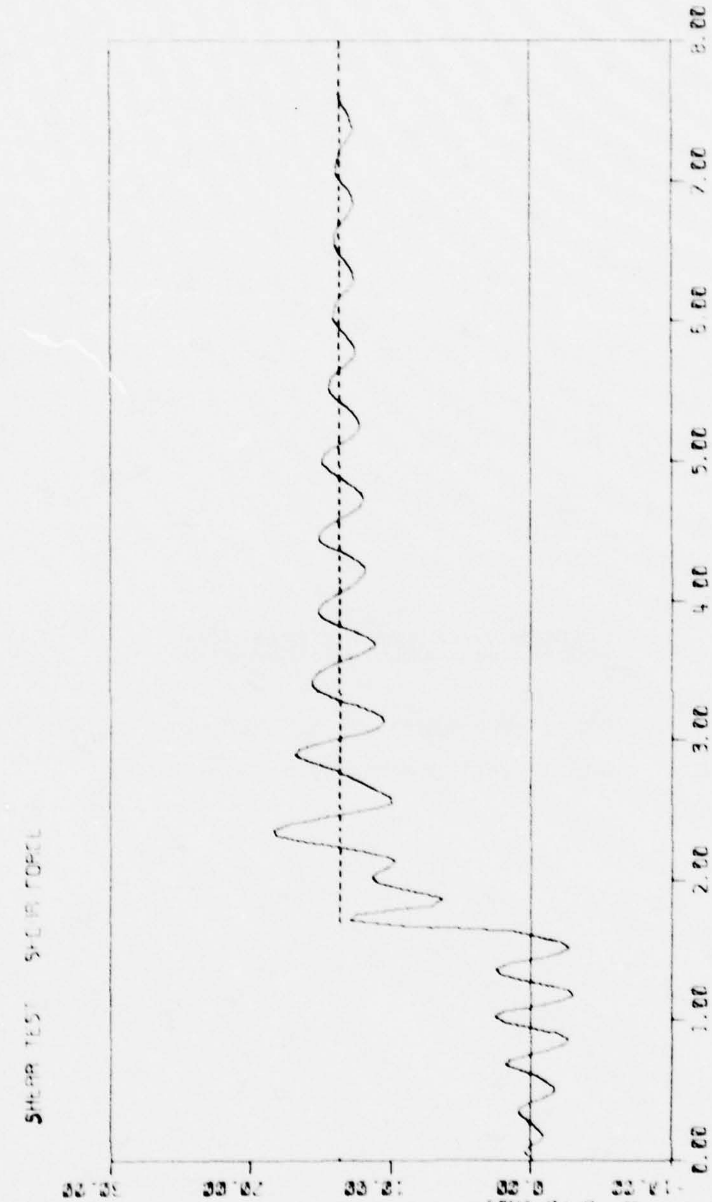


FIG. 6.17 TEST B

DAMES & MOORE

CHAPTER 7: OVERALL CONCLUSIONS

7.0 *The achievements of the study are evaluated and suggestions made for future work.*

7.1 ACHIEVEMENTS OF THE STUDY

The main object of the research was to demonstrate that the numerical schemes proposed for a fully deformable block program would actually work and give reasonably accurate results. This has now been accomplished. It has been shown that very little error is introduced into the calculation of sliding of rock joints by the various rezoning schemes used.

Although the new formulation is likely to be no more efficient than existing lagrange, finite-difference codes, it has two major advantages:

i) It is completely general, and can model any arbitrary jointing pattern, with no "tuning" needed by the user.

ii) Joints are modelled accurately, with no interpolation necessary at interfaces.

To be set against these advantages is the reputation that triangular zones have for being too "stiff".

The program, DBLOCK, that has been written to perform the verifications is only a "test-bed" program and does not include any of the housekeeping logic necessary for keeping track of interactions between

zones and joints. This logic can easily be built into a future program, since it will be based on that already tested in the original rigid-block program.

Several other goals have been accomplished: the original rigid-block program has been translated into Fortran, and has been extensively validated. It is in the form of a "base-line" program that can be used as a reference version for checking modified and extended versions against.

A new idea has been tried out, in which simple deformability is given to the blocks of the distinct element method. Each block is allowed three degrees of freedom to deform internally, with general constitutive laws being possible for the intact material. The method differs in a fundamental way from both finite elements and finite differences, and relies on the stiffnesses of joints to link neighbouring blocks, or zones. The new program, SDEM, is only slightly slower than the rigid-block program, RBM, and can be used in situations where the intact deformation of rock blocks, while not very large, cannot be neglected.

A modified version of RBM has been written that allows blocks to crack in response to the loads acting on them. The data structures have been changed so that blocks may divide and subdivide indefinitely (until limited by computer storage). A simple cracking criterion has been built into the program, based on semi-empirical results from point-load tests on irregular rock blocks. However, the program is structured so that the user may insert any other criterion with very little effort. It is

anticipated that the new program will be able to increase considerably the realism of simulations in which "hanging-up" of blocks would have occurred using the regular program, RBM.

A fairly extensive literature survey has been made on the properties and behaviour of rock joints. Based on the findings, a constitutive law has been proposed for rough rock joints, and coded up in the form of a Fortran subroutine called JOINT. The program seems to be capable of simulating the range of behaviour observed in the test results; it also gives plausible stress/strain curves for complex loading paths, for which test results do not exist. There is no doubt that when more comprehensive test results become available, the proposed constitutive law will need to be revised.

In summary, the work presented in this report should be regarded as the first phase in a continuing effort to understand and model jointed rock masses. Several tools have been developed, investigated and evaluated; in the next phases it is hoped that some or all of these tools will be used to simulate and predict real experiments on jointed rock. In this way the computer programs can be refined and corrected in the light of comparisons with experimental results.

7.2 APPLICABILITY AND USE OF THE COMPUTER PROGRAMS

Of all the programs that have been written during the present study, only RBM has been extensively validated. The other programs are only made available on the understanding that they are for experimental use only, and the results are not to be relied upon until further validations have been done and any bugs corrected.

RBM is applicable to jointed rock problems where the stresses are low, so that deformations at joints far exceed any intact rock deformations.

For situations involving higher stresses, SDEM should be used, up to the point where intact block deformations become comparable to joint deformations. At this stage SDEM will become inaccurate, and DBLOCK should be used instead.

If the rock is brittle and of low strength, cracks are probable, so that RBMC should be used. Parameter studies should be made in which the crack criterion is varied, since the mechanics of crack initiation is only approximately treated by RBMC.

7.3 SUGGESTIONS FOR FUTURE WORK

1. The programs developed in this study should be used to model existing laboratory tests on multiple-block systems, to determine the range of applicability of each program, and whether any important aspect of behaviour is being neglected.

2. RBM should be generally streamlined and made more efficient. In particular the program should include:

   i) the schemes embodied in SDEM and RBMC as options that can be "switched off" without degrading the efficiency of the standard RBM;

   ii) edge-to-edge contact, together with the constitutive law developed in Chapter 5;

   iii) logic to allow different properties for any joint or block;

   iv) water pressure in joints (without flow as a first option);

   v) optimised data structures (eliminating several redundant variables).

3. DBLOCK should be generalised, using the housekeeping logic of RBM, so that any geometry can be treated automatically. Other capabilities should be included, such as:

   i) a general constitutive law for the continuum zones (including non-associated plasticity);

   ii) a general constitutive law for joints;

   iii) non-reflecting boundaries for dynamic problems;

   iv) free-format input routine, general specification of boundary conditions and sophisticated graphical output displays;

   v) logic to allow cracks to propagate through the intact blocks, by creating new triangular zones as the crack moves through the continuum.

DBLOCK should also be extensively validated against existing experimental results on jointed rock.

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APPENDIX II : BIBLIOGRAPHY ON JOINT PROPERTIES AND JOINTED MODELS (PHYSICAL AND NUMERICAL)

The following abbreviations are used in Appendix II:

AIME	American Institute of Mining and Metallurgy
ARPA	Advanced Research Project Agency
ASCE	American Society of Civil Engineers
IJRM & MS	International Journal of Rock Mechanics and Mining Science
IMM	Institution of Mining and Metellurgy
ISRM	International Society for Rock Mechanics
JSM & FD	Journal of the Soil Mechanics and Foundation Division
U.S.B. Mines	United States Bureau of Mines

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APPENDIX III : INPUT COMMANDS FOR RBM AND EXAMPLE RUN

III-1 INPUT COMMANDS

This list of input cards must be read in conjunction with Section 2.4, which explains the use of the program in more detail. At present the input format is in fixed columns, unlike program SDEM, where free format can be used. Each card image consists of a command word, starting in column one, followed by a number of parameters, in successive 10-column fields, the first field starting in column 11.

DATA SET 1

COMMAND	PARAMETERS	COMMENTS
RESTART		Restart an old run from logical Unit 1. Go to data set 2.
START		Start a new run. This card must be followed by the two following cards:

1) heading card - any characters may be used
2) data card in (4I10,F10.0) format, giving:

NBLOKM = maximum number of blocks to be used
IBOXES = number of boxes in X-direction
JBOXES = number of boxes in y-direction
IBSIZE = size of single box (boxes are square)
TFRAC = fraction of critical time-step

DATA SET 2

COMMAND	PARAMETERS	COMMENTS
CREATE	NC, RHO, IFIX	Create a block with NC corners, density ρ and IFIX≠0 for a fixed block. This card must be followed by other card(s) giving NC corner coordinates: (X(I),Y(I),I=1,NC) in (8F10.0) Format. The coordinates must be given in a clockwise direction. A CREATE command must not be given after a CYCLE Command has been given.

COMMAND	PARAMETERS	COMMENTS
DUMP	LOC1, LOC2	Dump main array from LOC1 to LOC2. If LOC2 <0, dump by boxes, blocks & contacts.
CYCLE	NCYC	Execute NCYC time-steps
STOP		STOP. Saves problem on logical unit 1 unless a serious error has occurred.
PLOT		Plot current mesh.
GRAVITY	GRAVY, GRAVX	y and x accelerations due to gravity. Default values are GRAVY = -9.81, GRAVX = 0.0
STIFFNESS	STIFN, STIFS	Normal and shear contact stiffness. Default = 1×10^8.
DAMPING	$\lambda_{min}, f_{min}, I_\alpha, I_\beta$	$\left.\begin{matrix}\lambda_{min}\\ f_{min}\end{matrix}\right\}$ Rayleigh damping terms, defined in Section 2.4.6. If $I_\alpha = 1$, mass-proportional constant α is set to zero. If $I_\beta = 1$, stiffness-proportional constant β is set to zero. If $I_\alpha = I_\beta = 0$, normal Rayleigh damping is used.
FRICTION	FRIC	Friction coefficient for all edges.
ZERO		Set all velocities to zero.
RSET	IADR, VAL	Set A(IADR) to VAL.
ISET	IADR, IVAL	Set IA(IADR) to IVAL.
CHECK		Momentum and energy printout
LOAD	FX, FY, NB	Applies x and y forces to block NB centroid.

<u>EXAMPLE RUN OF RBM, WITH INPUT DATA AND OUTPUT LISTING.</u>

THE RUN IS FOR VALIDATION 5A, DESCRIBED IN CHAPTER 2.

INPUT DATA FOR EXAMPLE RUN OF RBM

```
START
VALIDATION 5 ... BLOCK FALLING ONTO PLANE
         2        10        10       100       0.1
CREATE            3        1.0         1
     100.0     100.0     900.0     300.0     900.0     100.0
CREATE            4        1.0         0
     700.0     500.0     700.0     600.0     800.0     600.0     800.0     500.0
GRAVITY       -9.81        0.0
STIFFNESS    1.0E7      1.0E7
DAMPING         0.5        5.0         1         0
FRICTION      0.300
PLOT
CYCLE          2500
DUMP             -1
STOP
```

OUTPUT LISTING FOR EXAMPLE RUN OF RBM

```
                              RBM - RIGID BLOCK MODEL.
                              ------------------------

VALIDATION 5 ... BLOCK FALLING ONTO PLANE

                              MAXIMUM NUMBER OF BLOCKS     2

                              BOXES IN X-DIRECTION        10
                              BOXES IN Y-DIRECTION        10
                              TOTAL NUMBER OF BOXES      100

                              SIZE OF SINGLE BOX         100
                              PROBLEM SIZE IN X-DIRN   1000.
                              PROBLEM SIZE IN Y-DIRN   1000.

                              TIMESTEP MULTIPLIER      0.100

+++ CREATE                3        1.0          1                                          +++
( 0.1000E+03,  0.1000E+03 ) (  0.4000E+03,  0.3000E+03 ) (  0.9000E+02,  0.1000E+03 ) (
XC,YC,MASS,MMOI :    6.333E+02   1.667E+02   8.000E+04   3.022E+09
+++ CREATE                4        1.0          0                                          +++
( 0.7000E+03,  0.5000E+03 ) (  0.7000E+03,  0.6000E+03 ) (  0.5000E+03,  0.6000E+03 ) (  0.8000E+03,  0.5000E+03 )
XC,YC,MASS,MMOI :    7.500E+02   5.500E+02   1.000E+04   1.667E+07
+++ GRAVITY           -9.81       0.0                                                      +++
+++ STIFFNESS          1.0E7      1.0E7                                                    +++
+++ DAMPING            0.5        5.0          1          0                                +++
         MASS DAMPING TERM SET TO ZERO
+++ FRICTION           0.300                                                               +++
+++ PLOT                                                                                   +++
+++ CYCLE             2500                                                                 +++
                               TIME INCREMENT =  6.3246E-03
                               DRIFT CORRECTION REQUIRED
+++ DUMP                -1                                                                 +++
---------------------------------------------------------------------------------------------------------------------
       M1        M2        M3        M4        M5        M6        M7    NBLOKS      NCYC     NEXPT   NCYCLE
        1         3        64       164       185       187      3000         2      2500       213     2500
      BOX      BLOCK     CORNER
       12        1          1
       15        2          2
       20        1          3
       25        2          3
       26        2          1
       36        2          4
       40        1          2
BLOCK DATA----------
NB IF NC        XC        YC     THETA      XDOT      YDOT      TDOT        DX        DY    DTHETA      AREA   INERTIA
             XFSUM     YFSUM      MSUM     XLOAD     YLOAD       COS       SIN

 1  3  3 6.33E+02  1.67E+02  0.00E-01  0.00E-01  0.00E-01  0.00E-01  0.00E-01  0.00E-01  0.00E-01  1.00E+04  3.02E+09
         3.79E+07 -2.36E+03 -1.64E+10  0.00E-01  0.00E-01  1.00E+00  0.00E-01 -5.33E+01 -6.67E+01  8.25E+02  2.07E+02
         1.33E+02  2.00E+02  2.67E+02 -6.67E+01  8.00E+02

 2  0  4 5.17E+02  2.58E+02 -1.67E-07 -2.40E+01 -5.99E+00  6.97E-07 -1.52E-01 -3.79E-02  4.41E-09  1.00E+04  1.67E+07
         4.02E+03  9.93E+04  3.52E+04  0.00E-01  0.00E-01 -2.44E-01  9.72E-01 -5.00E+01 -5.00E+01  1.00E+0  -5.00E+01
         5.00E+01  1.00E+02  5.00E+01  5.00E+01  1.00E+02  5.00E+01 -5.00E+01  1.00E+02
CONTACT DATA----------
      NOE       FRE       NPE       NFC       NHC      LINK
        S         N        FN        FS       SIN       COS       XCP       YCP

        1         0         1         1         2       187
 0.00E-01  0.00E-01  3.27E+04 -9.82E+03  2.43E-01  9.70E-01  5.78E+02  2.20E+02

        1         0         1         2         2         0
 0.00E-01  0.00E-01  6.25E+04 -1.87E+04  2.43E-01  9.70E-01  4.81E+02  1.95E+02
---------------------------------------------------------------------------------------------------------------------
+++ STOP                                                                                   +++
                               TOTAL CYCLES       2500
                               NO. UPDATES         418
                               A RESTART FILE HAS BEEN WRITTEN
```

APPENDIX IV: SUBROUTINE GUIDE TO RBM AND PROGRAM CHANGES

IV-1: SUBROUTINE GUIDE

RBM	Main program - calls SETUP, NEXT and CYCLE.
SETUP	Reads in initial problem definition, sets up data partitions and initialises data. It is called once only from RBM.
NEXT	Reads in commands and takes appropriate action. NEXT returns to RBM only when a number of cycles (time-steps) are to be executed. Before doing this for the first time, BOX is called.
BOX	When all blocks have been created, and some calculation cycles have been requested, BOX is called to perform the initial classification of block corners into boxes.
CYCLE	This is the driver for the main claculation cycle, and calls FORD and MOTION repeatedly for all blocks.
MOTION	Applies the law of motion for a single block. Velocities and displacements are updated from known centroid forces.
FORD	Applies the constitutive laws for a single block. Contact forces are evaluated from known displacements.
REBOX	Re-maps corners into boxes if necessary. REBOX is called from CYCLE, and is triggered when a block crosses an integer boundary.
UPDAT	Contacts are detected by UPDAT, which is called from CYCLE when cumulative displacements have exceeded a given limit.
GLX	Global x-coordinates from local.
GLY	Global y-coordinates from local.
DUMP	Printout of memory or lists - called from NEXT.
BPLOT	Plots a "snapshot" of the blocks (called from NEXT).
CHECK	Momentum and energy calculation (called from NEXT).
FINISH	Orderly termination of the program.

IV-2: PROGRAM CHANGES

Changes made to RBM since pre-release version 1.0 (September 1977). Please refer to listing in Appendix XII for line numbers.

1. Program RBM

i) Line 9: 62 in data statement (was 63).

2. Subroutine SETUP

i) This routine has been completely changed. It now reads just one card, instead of a set. The changes are mainly due to the elimination of co-ordinate scaling and shifting logic.

3. Subroutine NEXT

i) The command "LOAD" has been implemented, necessitating changes to lines 8, 16 and 123 to 127.

ii) Calls to date and time routines have been removed, necessitating changes to the WRITE statement on line 10 and format statement on line 135.

iii) All references to co-ordinate scaling and shifting have been removed, necessitating removal of lines preceding line 40, and modification of lines 44 to 48.

iv) DECODE statement on line 20 has been modified.

v) "AREA" in FORMAT statement 2002 has been changed to "MASS".

vi) Lines 99 to 113 changed to include full Rayleigh damping.

4. Subroutine BOX

i) Line 21: IBOXES replaces JBOXES.

5. Subroutine REBOX

i) Line 20: IBOXES replaces JBOXES.

6. Subroutine MOTION

i) Line 24: ABS inserted before B(5).

7. Subroutine UPDAT

i) Line 8: 0.001 changed to 1.0.

TOLB initialised to -0.01.

ii) Line 79: ICL = I2C + 20 replaces ICL = IA(I2C) + 20.

8. Common block / CBLOCK /

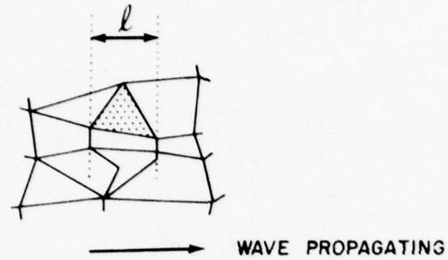
Changes made to reflect:

i) elimination of co-ordinate scaling and shifting;

ii) inclusion of mass damping.

APPENDIX V : DERIVATION OF EFFECTIVE MASSES - PROGRAM SDEM

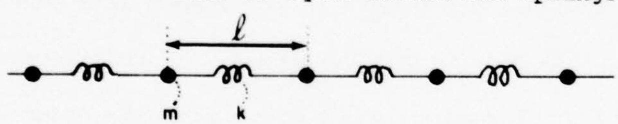
Consider a "continuum" of blocks through which a plane wave is propagating (assume the joints to be very stiff):



Let E* be the modulus appropriate to the type of wave (for example, G for shear waves, or $K + \frac{4}{3}G$ for p-waves). The velocity of propagation in a true continuum will be:

$$\sqrt{\frac{E^*}{\rho}} \quad \text{where } \rho \text{ is the density} \qquad \ldots \text{ V.1}$$

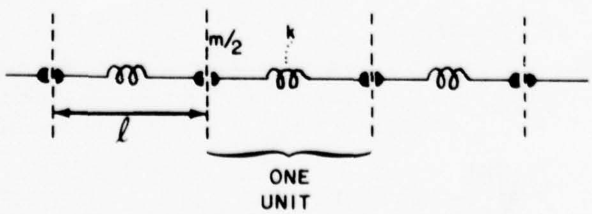
Consider now a line of equal masses and springs:



The velocity of wave propagation in this line is given by

$$C = \ell\sqrt{\frac{k}{m}}$$

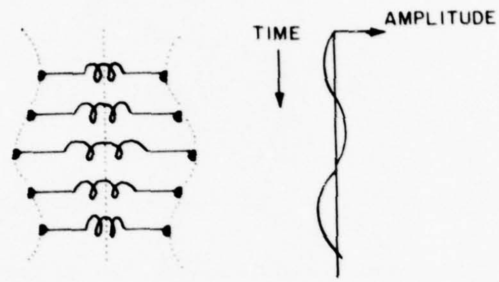
Suppose we now view the line as composed of individual mass/ spring units:



Individual units, if taken individually, will oscillate at a natural frequency of

$$\omega_o = \sqrt{\frac{2k}{m/2}} = 2\sqrt{\frac{k}{m}} \quad \text{with}$$

the following mode:



It is now possible to express the velocity of propagation in a mass/spring line in terms of the natural frequency of an individual unit:

$$C = \frac{\ell\omega_o}{2} \qquad \ldots \text{ V.2}$$

If the "continuum" of blocks is now viewed as a mass/spring system, we can establish an equivalence between the two systems. The natural frequency of individual blocks follows from the equations given in Section 3.4. In simplified form these are:

$$\dot{\varepsilon} := \dot{\varepsilon} - \frac{\sigma\Delta t}{m^e}$$

$$\overset{I}{\sigma} := \overset{I}{\sigma} + \dot{\varepsilon}E^*\Delta t$$

The natural frequency of this single degree of freedom system is:

$$\omega_b = \sqrt{\frac{E^*}{m^e}}$$

If these individual blocks are connected together to form a line, we can write down the velocity of propagation in terms of ω_b , using equation V.2.

$$C = \frac{\ell}{2}\sqrt{\frac{E^*}{m^e}}$$

But this must also be equal to the continuum wave speed given in V.1.

$$\frac{\ell}{2}\sqrt{\frac{E^*}{m^e}} = \sqrt{\frac{E^*}{\rho}}$$

$$m^e = \frac{\ell^2 \rho}{4}$$

$$\boxed{m^e = \frac{\ell^2 m}{4A}} \qquad \ldots \quad V.3.$$

where m = mass of block

A = area of block

The derivation above makes the assumption that all blocks having the same overall length in the direction of propagation will all have the same effective mass in that direction, and hence the same natural frequency. This seems physically reasonable, since for a plane wave to remain plane, the response time for blocks spanning the same distance should be the same, so that blocks oscillate in phase.

The four effective masses needed in Section 3.4 are:

$$m^e_{(i)} = \frac{m}{4A}(\ell_i)^2$$

where ℓ_i are the maximum block widths.

The effective masses derived above must necessarily be approximate, and are not intended for use in wave propagation problems. However, for dynamic problems where the wavelengths are larger than the typical overall problem dimensions, the formulation should be reasonable. In nearly-static problems, of course, the effective masses play no part.

APPENDIX VI : STRESS ROTATION CORRECTION TERMS

VI-1 Program SDEM

If a block, together with the forces acting on it, is rotated, the internal stresses, referred to local axes, are unaffected. However the stresses expressed in global coordinates will change. It is common in lagrangian finite-difference codes to apply stress rotation correction terms to the zone stresses at each time step in order to allow for this apparent stress change due to rotation. The correction terms are derived from the tensor transformation equations used to determine stresses in a new coordinate system (indicated by a bar) when they are known in an old system. These equations are as follows:

$$\bar{\sigma}_{ij} = \sigma_{\alpha\beta} \frac{\partial \bar{x}_i}{\partial x_\alpha} \frac{\partial \bar{x}_j}{\partial x_\beta} = \sigma_{\alpha\beta} J_{i\alpha} J_{j\beta} \qquad \ldots \text{ VI.1}$$

where J_{ij} is defined in section 3.4.

When the angle $\Delta\theta$ between the coordinate systems is small,

$J_{ij} = \delta_{ij} + \dot{R}_{ij}\,\Delta t$, discarding second order terms in $\Delta\theta$, and noting that $\Delta\theta = \dot{\theta}\Delta t$, with $\dot{R}_{ij}$ defined in section 3.4.

Using this expression for J_{ij} in VI.1 gives:

$$\bar{\sigma}_{ij} = \sigma_{\alpha\beta}(\delta_{i\alpha} + \dot{R}_{i\alpha}\Delta t)(\delta_{j\beta} + \dot{R}_{j\beta}\Delta t)$$

$$= \sigma_{ij} + (\sigma_{\alpha j}\dot{R}_{i\alpha} + \sigma_{i\beta}\dot{R}_{j\beta})\Delta t \qquad \ldots \text{ VI.2}$$

Format. The coordinates must be given in a clockwise direction. A CREATE command must not be given after a CYCLE Command has been given.

These new stresses correspond to a change in coordinate axes. However, in the case of a zone rotating, the coordinate axes remain fixed, and the zone rotates relative to the axes. Using a negative si in VI-2, and changing the repeated indices, gives the changes in zone stresses due to zone rotation:

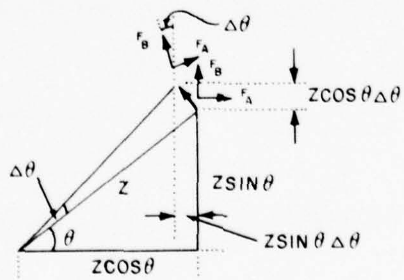
$$\Delta\sigma_{ij} = -(\sigma_{kj}\dot{R}_{ik} + \sigma_{ik}\dot{R}_{jk})\Delta t \qquad \ldots \quad \text{VI-3}$$

In the program SDEM, the block stresses are derived from the discrete forces acting on the block boundaries, using the equation:

$$\overset{A}{\sigma}_{ij} = \frac{\sum \overset{c}{F}_i \overset{c}{X}_j}{A} \qquad \ldots \quad \text{VI-4}$$

The following analysis was carried out to verify that giving a rotation to the discrete block/force system resulted in the same stress rotation correction terms as VI-3, derived for a continuum.

Consider two forces acting on a block that rotates through an angle $\Delta\theta$:



The stress that would be calculated by III-4 before and after the rotation are as follows:

stress	before rotation	after rotation
σ_{11}	$F\ z\cos\theta$	$(F\cos\Delta\theta - F\sin\Delta\theta)(z\cos\theta - z\sin\theta\Delta\theta)$
σ_{12}	$F\ z\sin\theta$	$(F\cos\Delta\theta - F\sin\Delta\theta)(z\sin\theta + z\cos\theta\Delta\theta)$
σ_{21}	$F\ z\cos\theta$	$(F\cos\Delta\theta + F\sin\Delta\theta)(z\cos\theta - z\sin\theta\Delta\theta)$
σ_{22}	$F\ z\sin\theta$	$(F\cos\Delta\theta + F\sin\Delta\theta)(z\sin\theta + z\cos\theta\Delta\theta)$

On multiplying out, and discarding second order terms, the differences between the stresses before and after rotation become:

$$\Delta\sigma_{11} = -(\sigma_{12} + \sigma_{21})\Delta\theta$$

$$\Delta\sigma_{12} = (\sigma_{11} - \sigma_{22})\Delta\theta$$

$$\Delta\sigma_{21} = (\sigma_{11} - \sigma_{22})\Delta\theta$$

$$\Delta\sigma_{22} = (\sigma_{12} + \sigma_{21})\Delta\theta$$

It can be seen that these correction terms are identical with those of VI-3. The terms are used in Section 3.4 in the calculation of internal stresses.

VI.2 Program DBLOCK

The correction of internal stresses due to rotation in program DBLOCK is identical to that described for SDEM (formula VI.3).

However the contact forces require a treatment different from that of the stresses since the correction is required to account for two mechanisms: a) the rotation of the surface normal, and b) the change in surface normals that occurs when a grid-point moves from one edge to another.

Let n_i and $\bar{n}_i$ be the old and new unit normals in the global coordinate system. Let f_i and $\bar{f}_i$ be the old and new components of the contact force in local coordinates (f_1 = shear force, f_2 = normal force). Lef F_i be the components of the contact force in the global coordinate system.

$$f_i = a_{ij} F_j$$

$$\bar{f}_i = \bar{a}_{ij} F_j$$

where $a_{2j} = n_j$, $a_{11} = a_{22}$, $a_{12} = -a_{21}$

$\bar{a}_{2j} = \bar{n}_j$, $\bar{a}_{11} = \bar{a}_{22}$, $\bar{a}_{12} = -\bar{a}_{21}$

Since a_{ij} is orthonormal,

$$a_{ij} \cdot a_{kj} = \delta_{ik}$$

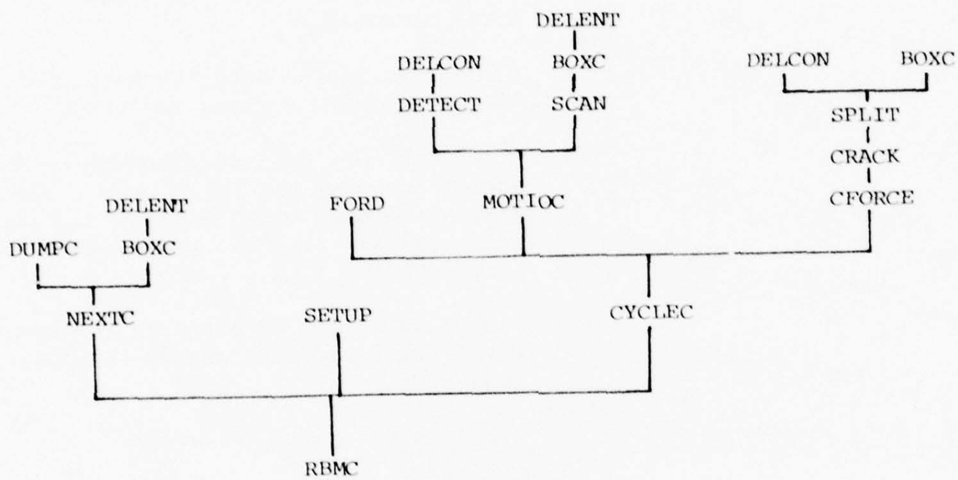
Then:

$$\bar{f}_i = \bar{a}_{ik} a_{jk} f_j$$

APPENDIX VII: SUBROUTINE GUIDE, PROGRAM RBMC

RBMC	Main program
SETUP	Initialization and input of problem size and constants.
NEXT	Processing of input commands. A return is made whenever command CYCLE is given.
BOX	Classifies blocks into the boxes that their edges and corners map into.
CYCLE	CYCLE controls the main calculation cycle; MOTIOC computes the law of motion for a single block; FORDC computes the constitutive law for the contacts around a single block.
CFORCE	Assembles a list of contacts for each block for subsequent use by the crack criterion.
CRACK	Embodies the crack criterion.
SPLIT	Introduces the crack into the selected block, and performs all necessary housekeeping duties.
BPLOT	Plots a "snapshot" of the problem geometry.
SCAN	Determines which boxes each block edge maps into.
DELENT	Deletes obsolete box entries.
DETECT	Detects and updates contacts for the two edges adjacent to a corner.
DELCON	Deletes obsolete contacts.
DUMP	Prints a dump of memory or linked list data.
LIMIT	Checks whether a request for more memory is possible.
EMPTYC	Creates a new contact data group.
EMPTYD	Creates a new "double".
FINISH	Terminates the program.

The main subroutines are called as follows:



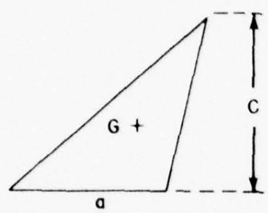
APPENDIX VIII: LIST OF SYMBOLS USED IN CHAPTER 6

The main symbols used in the text are:

$d(m\ n)$	=	distance from m to n
F_i	=	i^{th} component of the force
F_N	=	normal force
F_S	=	tangential force
K_E	=	kinetic energy
K_{NL}	=	normal stiffness during loading
K_{NU}	=	normal stiffness during unloading
K_S	=	shear stiffness
m_N	=	mass of node N
M_M	=	mass of zone M
n_i	=	i^{th} component of the unit normal
$O(\cdot)$	=	'of the order of'
R_{ij}	=	components of the rotation tensor
s	=	arc length
u_i	=	displacement tensor
$\bar{v}_N$	=	velocity vector for node N
v_p	=	P-wave velocity
x, y	=	two-dimensional orthogonal coordinate system
α, β	=	distance ratios
δ_{ij}	=	Kronecker delta
δ_N	=	normal displacement
δ_S	=	tangential displacement
Δ	=	increment
ε_{ij}	=	components of the strain tensor
ε_v	=	volumetric strain
λ, μ	=	Lamé constants
ρ	=	mass density
τ_{ij}	=	components of the stress tensor
τ^e_{ij}	=	elastic part of the stress tensor

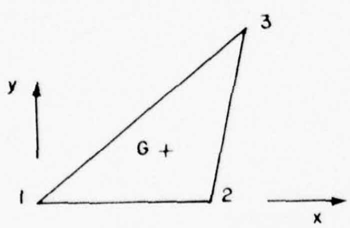
APPENDIX IX : PROPERTIES OF TRIANGLES USED IN PROGRAM DBLOCK

(1) The center of gravity of a triangle is at one third of the distance between any side and the opposite corner.



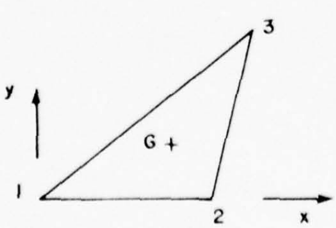
$$y_G = \frac{\int_0^c a\frac{c-y}{c}y\,dy}{\frac{ac}{2}} = \frac{c}{3} \quad \text{Q.E.D.}$$

(2) The coordinates of the center of gravity of a triangle are the average of those of its corners.



$$\frac{y_1+y_2+y_3}{3} = \frac{y_3}{3} = y_G \quad \text{Q.E.D.}$$

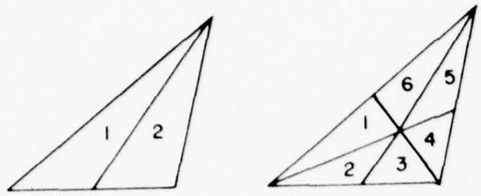
(3) The center of gravity of a triangle does not change if its mass is evenly lumped in its three corners.



TO PRESERVE THE FIRST MOMENT : $m_3 y_3 = M y_G$

$$\frac{m_3}{M} = \frac{y_G}{y_3} = \frac{1}{3} \quad \text{Q.E.D.}$$

(4) Each median divides a triangle in two triangles of equal area. The three medians divide a triangle in six triangles of equal area.



Obvious since the center of gravity is the intersection of all lines which split the mass of the triangle in two equal parts.

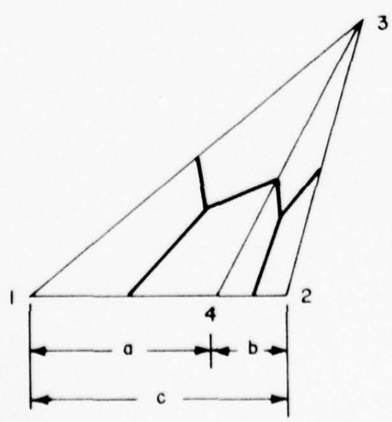
(5) The center of gravity of a triangle is the point of intersection of its medians.

Obvious

(6) The three medians provide a natural lumping of the mass of the triangle in its three corners which does not change the center of gravity.

Obvious

(7) If a new grid point (4) is created and the triangle $\widehat{(123)}$ split into two triangles $(\widehat{143}, \widehat{243})$ the assigned masses should be:



Let M = mass $\widehat{(123)}$ $\frac{a}{c} = \alpha$ $\frac{b}{c} = \beta$

$$m_1 = \frac{1}{3} \text{ mass } \widehat{(134)} = \alpha\frac{M}{3}$$

$$m_2 = \frac{1}{3} \text{ mass } \widehat{(234)} - \beta\frac{M}{3}$$

$$m_3 = \frac{1}{3} \text{ mass } \widehat{(134)} + \frac{1}{3} \text{ mass } \widehat{(234)} = \frac{M}{3}$$

$$m_4 = \frac{1}{3} \text{ mass } \widehat{(134)} + \frac{1}{3} \text{ mass } \widehat{(234)} = \frac{M}{3}$$

APPENDIX X : INPUT CARDS FOR PROGRAM DBLOCK

The required input stream is as follows:

1.	One card (6I10)	NMAX, MMAX, IMAX, IFLAG, KTOT, ICONT
	if IFLAG = 1, GO TO 6 if IFLAG = 2, GO TO 12	
2.	NMAX cards (4F10.0)	(X(N), Y(N), XD(N), YD(N), N=1,NMAX)
3.	NMAX cards (9F10.0)	(XX(M), YY(M), XY(M), AM(M), LAME1(M), LAME2(M), COHES(M), TANPHI(M), TANPSI(M), M=1,MMAX)
4.	NMAX cards (<IMAX>I10)	((MAN(N,I), I=1,IMAX), N=1,NMAX))
5.	MMAX cards (3I10)	((NAM(M,J), J=1,3), M=1,MMAX))
6.	LCONT cards (3I10, F10.0)	(IMP(L), N2M(L), N3M(L), XNC(L), L=1,LCONT)
7.	One card (5F10.0)	STNL, STNU, DN, STSH, XMU
8.	One card (I10, 4F10.0, 2I10)	NITER, FRAC, GRAV, ARAT, TFRAC, NPRI, NPLOT
9.	Two cards (8I10)	(ITPL(I),I=1,10)
10.	One card (2F10.0)	SCALEX, SCALEY
11.	One card (2F10.0)	RMIN, FMIN

END OF INPUT STREAM

12.	One card (I10)	NBLOCK
13.	One card (F10.0)	SCALE

The next two cards are repeated once for each block

NBLOCK times

14.	One card (I10)	NCORN
15.	NCORN cards (3I10)	(LIST(1,I), X(I), Y(I), I=1,NCORN)

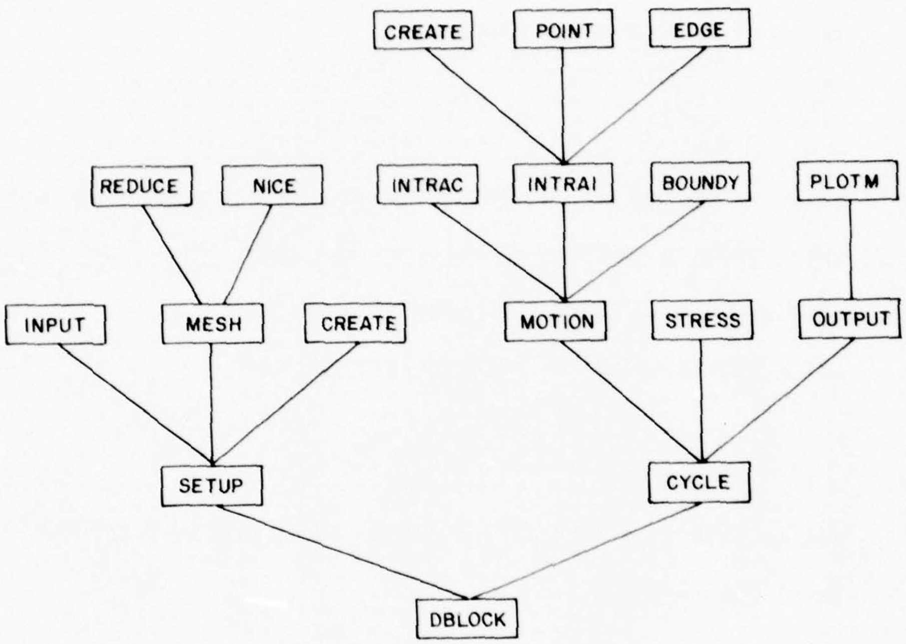
16.	One card (F10.0)	AMAXL

GO TO 6

The meaning of the FORTRAN variables is given in Appendix XVI.

APPENDIX XI: SUBROUTINE GUIDE - Program DBLOCK

The following tree illustrates the manner in which the different routines are called:



A brief description of each subroutine follows:

DBLOCK

- Is the driving routine for SETUP and CYCLE.

SETUP

- Reads in and prints all the information needed by the program.
- Initializes all variables.
- Assigns grid points masses.
- Computes the time step.
- In problems where more than one block exists SETUP also calls CREATE to create new nodes at the contacts as required.

CYCLE

- Drives the main interaction loop.
- Calls MOTION, STRESS every cycle; OUTPUT when needed.
- Prepares files for the plotter.

MESH

- Reads in the corners defining the geometry of each block and other information needed for creation of the mesh.
- Decomposes each block into triangles.
- Calls REDUCE and NICE, which refine the mesh.

REDUCE

- Splits triangles into two until all edges are smaller than a specified length.

NICE

- Rezones each node until the coordinates of all nodes (excluding those on the edge of the block coincide with the average of the coordinates of the surrounding nodes.

INPUT

- Creates a mesh consisting of a regular distribution of triangles.

CREATE

- Creates a new node and zone when a contact requires it.
- Redistributes mass and momentum while preserving their balance.

- Assigns mechanical properties to the new zone.
- Establishes the required logical links for the contact created and modifies those of other contacts which require changes due to the appearance of the new one.

MOTION

- Stresses are added to get the resultant force at each grid point. This provides accelerations; time integration yields velocities.

- Velocities are corrected by either one of two reasons:
  (a) if there is interaction between blocks, INTRAC is called;
  (b) boundary conditions in velocity are applied.

- Time integration of velocities yields displacments.

STRESS

- Computes incremental rotations and strains from velocities for each individual zone.

- Obtains the elastic stress increment, the viscous one (when damping exists) and the modification due to rotation; all 3 are compounded to obtain the new stresses.

OUTPUT

- Prints the main variables at pre-selected iteration numbers.

- Calls PLOTM to create a plot of the mesh at pre-selected iteration numbers.

- Creates files for plotting time histories of variables.

INTRAC

- Computes accelerations and velocities due to forces of interaction across blocks.

INTRA1

- This routine is the most complex in the program. A flow-chart of its functions is presented in Figure XI.1 to help visualize the procedures. As can be seen in the flow-chart, the routine is basically a loop extending to all contacts. For each one, relative displacements are computed, and the appropriate routine is called to calculate interacting forces from those displacements. Besides those functions, INTRA1 also breaks contacts, "tickles" nodes, deletes them or calls CREATE to provide new ones where needed. All the logic for the different types of rezoning is embodied in this routine.

BOUNDY

- Applies the boundary conditions in the form of velocities. These must be explicitly built into BOUNDY by means of FORTRAN statements.

<u>POINT</u>

- Computes forces of interaction from relative displacements across contacts using the laws in Section 6.2.6.1.

<u>EDGE</u>

- Computes forces of interaction from relative displacements across contacts using the laws in Section 6.2.6.2.

<u>PLOTM</u>

- Creates a plot of the complete finite difference mesh.

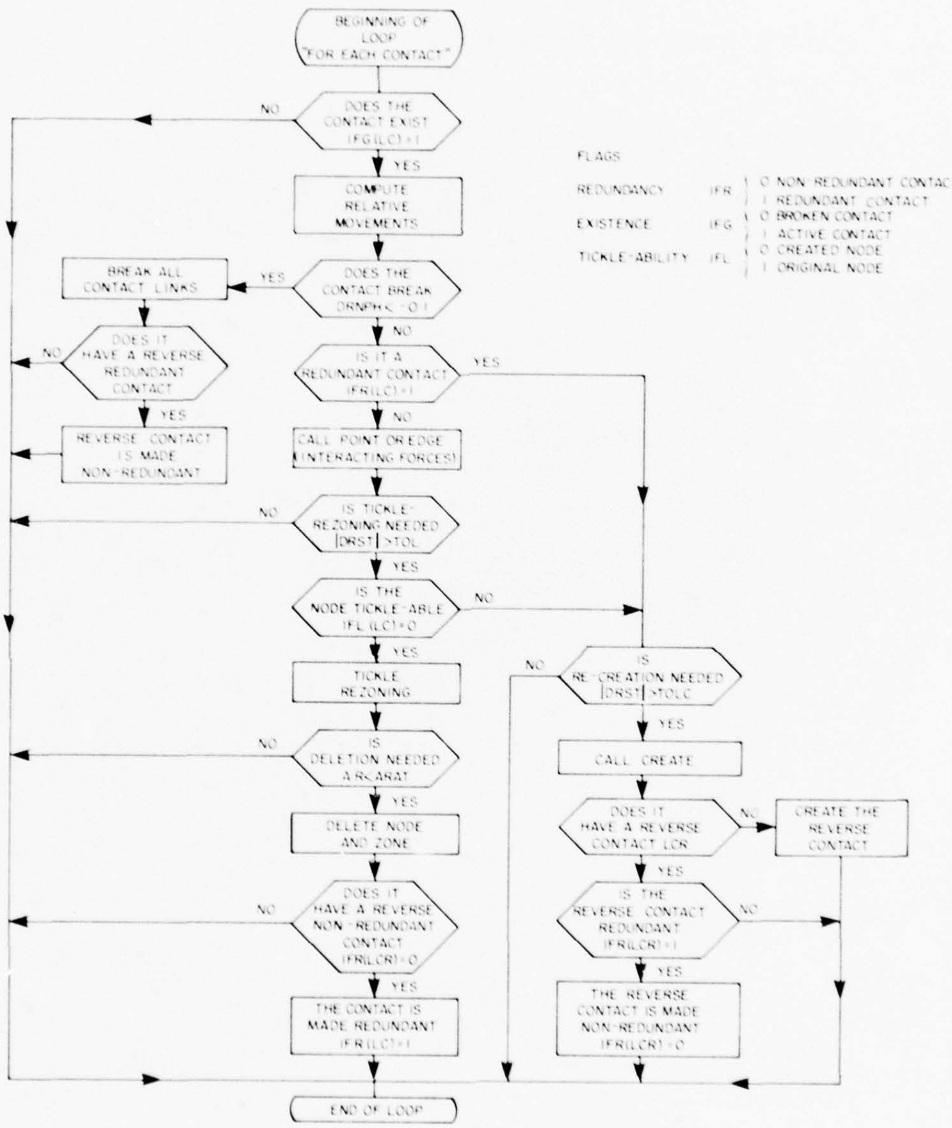


FIG. XI-1: FLOW CHART OF THE ROUTINE INTRA1

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APPENDIX XII : LIST OF VARIABLES AND PROGRAM LISTING FOR RBM

HED (20)	User supplied problem heading.
NBLOKM	Maximum number of blocks allowed. Sets storage according to this value.
NBOXES	Number of boxes (= IBOXES * JBOXES)
M1,M2...M7	Storage boundary markers.
NBLOKS	Number of blocks currently defined.
NCYC	Number of cycles requested on current CYCLE command.
MCYCLE	Current cycle number.
NEMPT	Pointer to start of empty list.
RFLAG	Reboxing flag. Indicates when reboxing is required.
UFLAG	Updating flag. Indicates when updating of coordinates is required.
EFLAG	Error flag. Indicates when an error condition has been detected. (Currently not used)
TFRAC	Fraction of critical timestep.
TDEL	Calculation timestep. TDEL is equal to the critical timestep* TFRAC.
IBOXES	Number of boxes in I-direction.
JBOXES	Number of boxes in J-direction.
BSIZE	Size of one box (boxes are square).
XSIZE	Width of box area (=IBOXES * BSIZE)
YSIZE	Height of box area (=JBOXES * BSIZE)
UDMAX	Maximum velocity detected in the current calculation cycle.
UMOST	Fictitious displacement, formed by summing UDMAX*TDEL and used to trigger the update flag.

STIFN	Normal contact stiffness: Currently is the same for all contacts.
STIFS	Shear contact stiffness. Currently is the same for all contacts.
FRIC	Contact coefficient of friction. Currently is the same for all contacts.
BETA	Stiffness-proportional damping constant.
BDT	BETA/TDEL
ALPHA	Mass-proportional damping constant
CON1 CON2	Constants used in mass-proportional damping.
GRAVX	Acceleration due to gravity in x-direction Units are acceleration units, not G's.
GRAVY	Acceleration due to gravity in y-direction.
LOC 1 LOC 2	Addresses passed to the DUMP routine for indicating the information to be printed.
NUPDAT	Counter of number of updates performed.
LBLOCK	Length of the commm block /CBLOCK/.

PROGRAM LISTING - RBM

```
FORTRAN IV-PLUS V02-51          17:00:21    16-FEB-78           PAGE 1
RBM.LST          /14/TR:BLOCKS/WR

0001          PROGRAM RBM
        C
        C-------------------------------------------------------------
        C------------------- RIGID BLOCK MODEL. ----------------------
        C------------------- FREELY TRANSLATED INTO FORTRAN BY -------
        C------------------- P.J.BERESFORD, FROM AN ORIGINAL PROGRAM -
        C------------------- BY P.A.CUNDALL. -------------------------
        C------------------- DAMES AND MOORE, LONDON. ----------------
        C------------------- VERSION 1.1, JANUARY 1978. --------------
        C-------------------------------------------------------------
        C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
             .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
             .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BUT,
             .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
             .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006          LOGICAL RFLAG,UFLAG,EFLAG
        C
0007          DATA STIFN,STIFS,FRIC,BETA/2*1.0E8,0.0,0.0/
0008          DATA GRAVY,GRAVX/-9.81,0.0/
0009          DATA M7,MCYCLE,NUPDAT,LBLOCK/3000,0,0,62/
0010          DATA RFLAG,UFLAG,EFLAG/.FALSE.,.TRUE.,.FALSE./
        C
0011          CALL PLOTST(.025,'CM')
0012          CALL SETUP
0013       10 CALL NEXT
0014          CALL CYCLE
0015          GOTO 10
        C
0016          END
```

```
FORTRAN IV-PLUS V02-51          17:00:32    16-FEB-78            PAGE 3
RBM.LST          /14/TR:BLOCKS/WR

0001          SUBROUTINE SETUP
        C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
         .                    NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
         .                    TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
         .                    UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
         .                    CON1,CON2,NVARB,NFRAG,NBR,NPR,
         .                    GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006          LOGICAL RFLAG,UFLAG,EFLAG
        C
0007          WRITE(6,2000)
0008          READ(5,1000) WORD
        C
0009          IF(WORD.EQ.4HSTAR) GOTO 20
0010          IF(WORD.EQ.4HREST) GOTO 10
        C
0011          WRITE(6,3000)
0012          STOP
        C
        C--------- 'RESTART' RUN ---
0013       10 READ(1) (HED(I),I=1,LBLOCK)
0014          READ(1) (A(I),I=1,M7)
0015          WRITE(6,2001) HED,MCYCLE
0016          RETURN
        C
        C--------- 'START' RUN ---
0017       20 READ(5,1001) HED,NBLOKM,IBOXES,JBOXES,IBSIZE,TFRAC
        C
0018          NBOXES=IBOXES*JBOXES
0019          BSIZE=IBSIZE
0020          XSIZE=IBOXES*BSIZE
0021          YSIZE=JBOXES*BSIZE
        C
0022          WRITE(6,2002) HED,NBLOKM,IBOXES,JBOXES,NBOXES,
         .                  IBSIZE,XSIZE,YSIZE,TFRAC
        C
        C------------------- INITIALISE SOME VARIABLES ---
0023          UMOST=0.0
0024          NBLOKS=0
0025          M1=1
0026          M2=M1+NBLOKM
0027          M3=M2
0028          RETURN
        C
0029     1000 FORMAT(A4)
0030     1001 FORMAT(20A4/4I10,F10.0)
0031     2000 FORMAT(30X,25H RBM - RIGID BLOCK MODEL./
         .          30X,25H -------------------------/)
0032     2001 FORMAT(1X,20A4//30X,30HRESTART RUN. CURRENT CYCLES ...,I10//)
0033     2002 FORMAT(1X,20A4//
         .          30X,24HMAXIMUM NUMBER OF BLOCKS,I5//
         .          30X,24HBOXES IN X-DIRECTION    ,I5/
```

```
FORTRAN IV-PLUS V02-51          17:00:32    16-FEB-78           PAGE 4
RBM.LST         /I4/TR:BLOCKS/WR

            .       30X,24HBOXES IN Y-DIRECTION     ,I5/
            .       30X,24HTOTAL NUMBER OF BOXES    ,I5//
            .       30X,24HSIZE OF SINGLE BOX       ,I5/
            .       30X,24HPROBLEM SIZE IN X-DIRN   ,F6.0/
            .       30X,24HPROBLEM SIZE IN Y-DIRN   ,F6.0//
            .       30X,24HTIMESTEP MULTIPLIER      ,F6.3//)
0034     3000 FORMAT(48H *** ERROR : 'START' OR 'RESTART' CARD NOT FOUND)
        C
0035          END
```

```
FORTRAN IV-PLUS V02-51          17:00:56    16-FEB-78           PAGE 6
RBM.LST         /14/TR:BLOCKS/WR

0001          SUBROUTINE NEXT
        C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
             .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
             .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
             .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
             .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006          LOGICAL RFLAG,UFLAG,EFLAG
        C
0007          DIMENSION CARD(20),WORD(20),X(50),Y(50)
        C
0008          DATA WORD /4HCREA,4HDELE,4HDUMP,4HCYCL,4HSTOP,
             .           4HPLOT,4H****,4HRSET,4HISET,4HCHEC,
             .           4HGRAV,4HSTIF,4HDAMP,4HFRIC,4HZERO,
             .           4HLOAD,4HZZZZ,4HZZZZ,4HZZZZ,4HZZZZ/
        C
        C------------------- READ NEXT CARD ---
0009       10 READ(5,1000) CARD
0010          WRITE(6,2000) CARD
0011          DO 20 I=1,20
0012          IF(CARD(1).EQ.WORD(I)) GOTO 30
0013       20 CONTINUE
0014          WRITE(6,3000)
0015          GOTO 10
        C------------------- JUMP TO APPROPRIATE CODE ---
0016       30 GOTO (100,150,200,250,300,
             .      350,400,450,500,550,
             .      600,650,700,750,800,
             .      850, 10, 10, 10, 10), I
        C
0017       40 WRITE(6,3001)
0018          GOTO 10
        C------------------- CREATE A NEW BLOCK ---
0019      100 NBLOKS=NBLOKS+1
0020          DECODE(40,1001,CARD) NC,RHO,JFIX
0021          READ(5,1002) (X(I),Y(I),I=1,NC)
0022          WRITE(6,2001) (X(I),Y(I),I=1,NC)
0023          I2=M3
0024          IA(NBLOKS)=I2
0025          IF(JFIX.NE.0) IA(I2)=1
0026          IA(I2+1)=NC
0027          A(I2+18)=1.0
0028          A(I2+19)=0.0
        C------------------- AREA AND CENTROID OF THIS BLOCK ---
0029          AREA=(X(1)-X(NC))*(Y(1)+Y(NC))
0030          YC=(X(1)-X(NC))*((Y(1)-Y(NC))*(Y(1)+2.0*Y(NC))+3.0*Y(NC)**2)
0031          XC=(Y(1)-Y(NC))*((X(1)-X(NC))*(X(1)+2.0*X(NC))+3.0*X(NC)**2)
0032          DO 110 I=2,NC
0033          AREA=AREA+(X(I)-X(I-1))*(Y(I)+Y(I-1))
0034          YC=YC+(X(I)-X(I-1))*((Y(I)-Y(I-1))*(Y(I)+2.0*Y(I-1))
             .     +3.0*Y(I-1)**2)
```

```
FORTRAN IV-PLUS V02-51          17:00:56    16-FEB-78           PAGE 7
RBM.LST          /I4/TR:BLOCKS/WR

          XC=XC+(Y(I)-Y(I-1))*((X(I)-X(I-1))*(X(I)+2.0*X(I-1))
     .        +3.0*X(I-1)**2)
    110 CONTINUE
        AREA=0.5*AREA
        YC=YC/(6.0*AREA)
        XC=-XC/(6.0*AREA)
        A(I2+2)=XC
        A(I2+3)=YC
        A(I2+11)=AREA*RHO
C------------------- LOCAL COORDINATES FOR THIS BLOCK ---
        M3=M3+20
        A(M3)=X(1)-XC
        A(M3+1)=Y(1)-YC
        DO 120 I=2,NC
        A(M3+3)=X(I)-XC
        A(M3+4)=Y(I)-YC
        A(M3+2)=SQRT((A(M3+3)-A(M3))**2+(A(M3+4)-A(M3+1))**2)
    120 M3=M3+3
        A(M3+2)=SQRT((A(I2+20)-A(M3))**2+(A(I2+21)-A(M3+1))**2)
        M3=M3+3
C------------------- MOMENT OF INERTIA ---
        RMOI=0.0
        IC=I2+20
        DO 130 NP=2,NC
        AREA=A(IC)*A(IC+1) + (A(IC+3)-A(IC))*(A(IC+4)+A(IC+1))
     .        - A(IC+3)*A(IC+4)
        AREA=0.5*AREA
        TEMP=A(IC)**2+A(IC+1)**2+A(IC+3)**2+A(IC+4)**2
     .        +A(IC)*A(IC+3)+A(IC+1)*A(IC+4)
        RMOI=RMOI+AREA*TEMP/6.0
    130 IC=IC+3
        AREA=A(IC)*A(IC+1) + (A(I2+20)-A(IC))*(A(I2+21)+A(IC+1))
     .        - A(I2+20)*A(I2+21)
        AREA=0.5*AREA
        TEMP=A(I2+20)**2+A(I2+21)**2+A(IC)**2+A(IC+1)**2
     .        +A(I2+20)*A(IC)+A(I2+21)*A(IC+1)
        RMOI=RMOI+AREA*TEMP/6.0
        A(I2+12)=RMOI*RHO
C
        WRITE(6,2002) XC,YC,A(I2+11),A(I2+12)
        GOTO 10
C------------------- DELETE A BLOCK ---
    150 GOTO 40
C------------------- DUMP MEMORY AS REQUESTED ---
    200 DECODE(30,1003,CARD) LOC1,LOC2
        IF(LOC2.NE.0) GOTO 220
        LOC2=LOC1
        LOC1=1
    220 CALL DUMP
        GOTO 10
C------------------- CYCLE ROUND MOTION AND FORD ---
    250 DECODE(20,1001,CARD) NCYC
        IF(MCYCLE.EQ.0) CALL BOX
        RETURN
C------------------- STOP COMMAND ---
    300 CALL FINISH
```

```
FORTRAN IV-PLUS V02-51          17:00:56    16-FEB-78            PAGE 8
RBM.LST          /I4/TR:BLOCKS/WR

      C------------------- PLOT COMMAND ---
        350 CALL BPLOT
            GOTO 10
      C------------------- RETURN TO PHASE 1 ---
        400 CALL SETUP
            GOTO 10
      C------------------- SET REAL DATA ---
        450 DECODE(30,1004,CARD) IADR,VAL
            IF(IADR.LE.0.OR.IADR.GT.M7) GOTO 480
            A(IADR)=VAL
            GOTO 10
        480 WRITE(6,3002)
            GOTO 10
      C------------------- SET INTEGER DATA ---
        500 DECODE(30,1003,CARD) IADR,IVAL
            IF(IADR.LE.0.OR.IADR.GT.M7) GOTO 480
            IA(IADR)=IVAL
            GOTO 10
      C------------------- MOMENTUM & ENERGY CHECK ---
        550 CALL CHECK
            GOTO 10
      C------------------- GRAVITY ---
        600 DECODE(30,1005,CARD) GRAVY,GRAVX
            GOTO 10
      C------------------- CONTACT STIFFNESSES ---
        650 DECODE(30,1005,CARD) STIFN,STIFS
            GOTO 10
      C------------------- RAYLEIGH DAMPING ---
        700 DECODE(50,1006,CARD) FRAC,FREQ,IF1,IF2
            PI2=8.0*ATAN(1.0)
            ALPHA=PI2*FRAC*FREQ
            BETA=FRAC/(PI2*FREQ)
            IF(IF1.EQ.0) GO TO 710
            ALPHA=0.0
            WRITE(6,3003)
        710 IF(IF2.EQ.0) GO TO 720
            BETA=0.0
            WRITE(6,3004)
        720 IF(MCYCLE.EQ.0) GO TO 10
            BDT=BETA/TDEL
            CON1=1.0-ALPHA*TDEL/2.0
            CON2=1.0/(1.0+ALPHA*TDEL/2.0)
            GOTO 10
      C------------------- FRICTION COEFFICIENT ---
        750 DECODE(20,1005,CARD) FRIC
            GOTO 10
      C------------------- ZERO ALL VELOCITIES ---
        800 DO 820 NB=1,NBLOKS
            I2=IA(NB)
            A(I2+5)=0.0
            A(I2+6)=0.0
            A(I2+7)=0.0
        820 CONTINUE
            GOTO 10
      C------------------- SET BLOCK LOADS ---
        850 DECODE(40,1006,CARD) FX,FY,NB
```

```
      I2=IA(NB)
      A(I2+16)=FX
      A(I2+17)=FY
      GOTO 10
C
 1000 FORMAT(20A4)
 1001 FORMAT(10X,I10,F10.0,I10)
 1002 FORMAT(8F10.0)
 1003 FORMAT(10X,2I10)
 1004 FORMAT(10X,I10,F10.0)
 1005 FORMAT(10X,2F10.0)
 1006 FORMAT(10X,2F10.0,2I10)
 2000 FORMAT(1X,4H+++ ,20A4,4H +++)
 2001 FORMAT(1X,4(1H(,E12.4,1H,,E12.4,3H ) ))
 2002 FORMAT(18H XC,YC,MASS,RMOI :,1P4E12.3)
 3000 FORMAT(28H !!! ERROR : ILLEGAL COMMAND)
 3001 FORMAT(34H !!! ERROR : COMMAND NOT AVAILABLE)
 3002 FORMAT(33H !!! ERROR : ADDRESS OUT OF RANGE)
 3003 FORMAT(10X,29HMASS DAMPING TERM SET TO ZERO)
 3004 FORMAT(10X,34HSTIFFNESS DAMPING TERM SET TO ZERO)
C
      END
```

```
FORTRAN IV-PLUS V02-51          17:03:35    16-FEB-78           PAGE 11
RBM.LST         /I4/TR:BLOCKS/WR

            SUBROUTINE BOX
      C
      C-------------------- ALL BLOCKS HAVE BEEN CREATED.
      C-------------------- BLOCKS CAN NOW BE BOXED -----
      C
            COMMON A(3000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
           .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
           .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
           .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
           .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
            LOGICAL RFLAG,UFLAG,EFLAG
      C
            M4=M3+NBOXES
            M5=M4
      C-------------------- INITIALISE BOX POINTERS ---
            I1=M4-1
            DO 10 I=M3,I1
         10 IA(I)=0
      C-------------------- LOOP ON EACH BLOCK ---
            DO 50 NB=1,NBLOKS
            I2=IA(NB)
            NC=IA(I2+1)
            IC=I2+20
      C-------------------- LOOP ON EACH CORNER ---
            DO 40 NP=1,NC
            X=A(I2+2)+A(IC)
            Y=A(I2+3)+A(IC+1)
            IBOX=MIN0(IFIX(X/BSIZE)+1,IBOXES)
            JBOX=MIN0(IFIX(Y/BSIZE),JBOXES-1)
            NBOX=JBOX*IBOXES+IBOX
            I3=M3+NBOX-1
            IA(M5+2)=IA(I3)
            IA(I3)=M5
            IA(M5)=NP
            IA(M5+1)=NB
            M5=M5+3
            IC=IC+3
         40 CONTINUE
      C
         50 CONTINUE
      C
            M6=M5+NBLOKM
            DO 60 I=M5,M6
         60 IA(I)=0
      C-------------------- CREATE EMPTY LIST TO END OF MEMORY ---
            NEMPT=M6
            I6=M6+4
            DO 80 I=I6,M7,13
            J=I
            IA(I)=I+9
         80 CONTINUE
```

```
FORTRAN IV-PLUS V02-51          17:03:35    16-FEB-78            PAGE 12
RBM.LST          /I4/TR:BLOCKS/WR

            IA(J)=0
      C-------------------- DETERMINE TIMESTEP ---
            TDEL=1.0E20
            DO 100 NB=1,NBLOKS
            I2=IA(NB)+11
            TN=2.0*SQRT(A(I2)/STIFN)
            TS=2.0*SQRT(A(I2)/STIFS)
            TDEL=AMIN1(TDEL,TN,TS)
        100 CONTINUE
            TDEL=TDEL*TFRAC
            WRITE(6,2000) TDEL
      C-------------------- SET UP DAMPING TERMS ---
            BDT=BETA/TDEL
            CON1=1.0-ALPHA*TDEL/2.0
            CON2=1.0/(1.0+ALPHA*TDEL/2.0)
      C
            RETURN
      C
       2000 FORMAT(30X,17H TIME INCREMENT =,1PE12.4)
      C
            END
```

- Applies the boundary conditions in the form of velocities. These must be explicitly built into BOUNDY by means of FORTRAN statements.


```
FORTRAN IV-PLUS V02-51          17:04:30    16-FEB-78           PAGE 14
RBM.LST         /14/TR:BLOCKS/WR


0001          SUBROUTINE CYCLE
        C
        C------------------- DRIVER FOR ITERATIONS ---
        C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
             .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
             .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
             .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
             .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006          LOGICAL RFLAG,UFLAG,EFLAG
        C
0007          DO 100 NCYCLE=1,NCYC
0008          MCYCLE=MCYCLE+1
        C------------------- UPDATE IF NECESSARY ---
0009          IF(UFLAG) CALL UPDAT
        C------------------- SCAN ALL BLOCKS ---
0010          UDMAX=0.0
0011          DO 20 NB=1,NBLOKS
0012          IB=IA(NB)
0013          CALL MOTION(A(IB))
0014          IF(RFLAG) CALL REBOX(NB)
0015       20 CONTINUE
        C------------------- EXIT IF NOTHING MOVED ---
0016          IF(UDMAX.EQ.0.0) GOTO 110
        C------------------- UPDATE CONTACTS ? ---
0017          UMOST=UMOST+UDMAX*TDEL
0018          IF(UMOST.LT.1.0) GOTO 30
        C------------------- YES ---
0019          UFLAG=.TRUE.
        C------------------- SCAN ALL CONTACTS ---
0020       30 DO 50 NB=1,NBLOKS
0021          IBE=IA(NB)
0022          J6=M5+NB-1
0023       40 I6=IA(J6)
0024          IF(I6.EQ.0) GOTO 50
0025          JBC=IA(I6+3)
0026          IBC=IA(JBC)
0027          CALL FORD(A(I6),A(IBC),A(IBE))
0028          J6=I6+4
0029          GOTO 40
0030       50 CONTINUE
        C
        C------------------- END CYCLE LOOP ---
        C
0031      100 CONTINUE
        C
0032      110 CONTINUE
        C
0033          RETURN
        C
0034          END
```

```
FORTRAN IV-PLUS V02-51          17:05:00    16-FEB-78           PAGE 16
RBM.LST          /14/TR:BLOCKS/WR


0001            SUBROUTINE MOTION(B)
          C
          C-------------------- LAW OF MOTION FOR A SINGLE BLOCK ---
          C
0002            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
               .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
               .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
               .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
               .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
               .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0003            LOGICAL RFLAG,UFLAG,EFLAG
0004            DIMENSION B(1)
0005            EQUIVALENCE (FIX,JFIX)
          C
0006            FIX=B(1)
          C-------------------- IS THIS BLOCK FIXED ? ---
0007            IF(JFIX.NE.0) RETURN
          C-------------------- NO ---
          C-------------------- VELOCITIES FROM ACCELERATIONS ---
0008            B(6)=(B(6)*CON1+(B(14)/B(12)+GRAVX)*TDEL)*CON2
0009            UDMAX=AMAX1(UDMAX,ABS(B(6)))
0010            B(7)=(B(7)*CON1+(B(15)/B(12)+GRAVY)*TDEL)*CON2
0011            UDMAX=AMAX1(UDMAX,ABS(B(7)))
0012            B(8)=(B(8)*CON1+(B(16)/B(13))*TDEL)*CON2
0013            B(14)=B(17)
0014            B(15)=B(18)
0015            B(16)=0.0
          C-------------------- DISPLACEMENTS FROM VELOCITIES ---
0016            IBX=B(3)
0017            IBY=B(4)
0018            B(9)=B(6)*TDEL
0019            B(10)=B(7)*TDEL
0020            B(11)=B(8)*TDEL
0021            B(3)=B(3)+B(9)
0022            B(4)=B(4)+B(10)
0023            B(5)=B(5)+B(11)
          C-------------------- DO WE NEED TO REBOX ? ---
0024            IF(IBX.EQ.IFIX(B(3)).AND.IBY.EQ.IFIX(B(4))
               .  .AND.ABS(B(5)).LT.0.01) GOTO 100
          C-------------------- YES ---
0025            RFLAG=.TRUE.
0026            B(5)=0.0
          C-------------------- UPDATE COS AND SIN FOR THIS BLOCK ---
0027        100 TEMP=B(19)
0028            B(19)=B(19)-B(11)*B(20)
0029            B(20)=B(20)+B(11)*TEMP
          C-----------------------------------------------------------
0030            RETURN
          C
0031            END
```

```
FORTRAN IV-PLUS V02-51          17:05:28     16-FEB-78            PAGE 18
RBM.LST          /I4/TR:BLOCKS/WR

      SUBROUTINE FORD(C,BC,BE)
C
C-------------------- FORCE DISPLACEMENT LAW FOR SINGLE CONTACT ---
C
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
     .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
     .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
     .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
     .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
      LOGICAL RFLAG,UFLAG,EFLAG
      DIMENSION C(1),BC(1),BE(1)
C
C-------------------- INCREMENTAL GLOBAL DISPLACEMENTS ---
      DUY=BC(10)-BE(10)+BC(11)*(C(12)-BC(3))-BE(11)*(C(12)-BE(3))
      DUX=BC( 9)-BE( 9)-BC(11)*(C(13)-BC(4))+BE(11)*(C(13)-BE(4))
C-------------------- NORMAL COORDINATES ---
      DUS=DUX*C(11)+DUY*C(10)
      DUN=DUY*C(11)-DUX*C(10)
C-------------------- NORMAL FORCE ---
      DFN=-DUN*STIFN
      C(8)=C(8)+DFN
C-------------------- TEST FOR TENSION ---
      IF(C(8).GE.0.0) GOTO 20
      C(8)=0.0
      C(9)=0.0
      DN=0.0
      DS=0.0
      GOTO 60
C-------------------- SHEAR FORCE ---
   20 DFS=DUS*STIFS
      C(9)=C(9)+DFS
      FRICF=FRIC*C(8)
      IF(ABS(C(9)).LE.FRICF) GOTO 40
      C(9)=SIGN(FRICF,C(9))
      DS=0.0
      GOTO 50
C-------------------- DASHPOT FORCES ---
   40 DS=BDT*DFS
   50 DN=BDT*DFN
C-------------------- GLOBAL CONTACT FORCES ---
   60 FYC=(C(9)+DS)*C(10)-(C(8)+DN)*C(11)
      FXC=(C(9)+DS)*C(11)+(C(8)+DN)*C(10)
C-------------------- ADD CONTRIBUTION TO BLOCK FORCES ---
      BC(14)=BC(14)-FXC
      BC(15)=BC(15)-FYC
      BC(16)=BC(16)-(FYC*(C(12)-BC(3))-FXC*(C(13)-BC(4)))
      BE(14)=BE(14)+FXC
      BE(15)=BE(15)+FYC
      BE(16)=BE(16)+(FYC*(C(12)-BE(3))-FXC*(C(13)-BE(4)))
C
      RETURN
C
      END
```

```
      SUBROUTINE REBOX(NB)
C
C-------------------- ROUTINE TO REBOX A SINGLE BLOCK ---
C
      COMMON A(3000)
      DIMENSION IA(1)
      EQUIVALENCE (A,IA)
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
     .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
     .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
     .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
     .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
      LOGICAL RFLAG,UFLAG,EFLAG
C
      IB=IA(NB)
      NC=IA(IB+1)
C-------------------- SCAN EACH CORNER OF THE BLOCK ---
      IC=IB+20
      DO 100 NP=1,NC
C-------------------- ARE WE AT EDGE OF DOMAIN ? ---
      IF(GLX(A(IB),IC).GT.0.0.AND.GLX(A(IB),IC).LT.XSIZE.AND.
     .   GLY(A(IB),IC).GT.0.0.AND.GLY(A(IB),IC).LT.YSIZE) GOTO 20
C-------------------- YES, SET MASTER FIX FLAG ---
      IA(IB)=2
      A(IB+5)=0.0
      A(IB+6)=0.0
      A(IB+7)=0.0
      A(IB+8)=0.0
      A(IB+9)=0.0
      A(IB+10)=0.0
      GOTO 900
C-------------------- NO, WHICH BOX SHOULD CORNER BE IN ? ---
   20 NBOX=IFIX(GLX(A(IB),IC)/BSIZE)+IFIX(GLY(A(IB),IC)/BSIZE)*IBOXE:
C-------------------- SEARCH THIS BOX ---
      J4N=M3+NBOX-1
   30 I4N=IA(J4N)
      IF(I4N.EQ.0) GOTO 40
      IF(NB.EQ.IA(I4N+1).AND.NP.EQ.IA(I4N)) GOTO 100
      J4N=I4N+2
      GOTO 30
C-------------------- SEARCH THE SURROUNDING BOXES ---
   40 NXL=MAX0(MOD(NBOX-1,IBOXES),1)
      NXU=MIN0(NXL+2,IBOXES)
      NYL=MAX0(NBOX/IBOXES,1)
      NYU=MIN0(NYL+2,JBOXES)
      DO 80 JBOX=NYL,NYU
      MBOX=(JBOX-1)*IBOXES+NXL-1
      DO 70 IBOX=NXL,NXU
      MBOX=MBOX+1
      IF(MBOX.EQ.NBOX) GOTO 70
      J4M=M3+MBOX-1
   50 I4M=IA(J4M)
      IF(I4M.EQ.0) GOTO 70
      IF(NB.EQ.IA(I4M+1).AND.NP.EQ.IA(I4M)) GOTO 60
```

```
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            J4M=I4M+2
            GOTO 50
      C------------------- SWAP ENTRIES FOR THIS CORNER ---
         60 IA(J4M)=IA(I4M+2)
            IA(J4N)=I4M
            IA(I4M+2)=0
            GOTO 100
      C------------------- END OF SURROUNDING BOXES SCAN ---
         70 CONTINUE
         80 CONTINUE
            WRITE(6,3000) NP,NB
            EFLAG=.TRUE.
            CALL FINISH
      C------------------- END OF CORNERS SCAN ---
        100 IC=IC+3
      C
      C------------------- EXIT ---
        900 RFLAG=.FALSE.
            RETURN
      C
       3000 FORMAT(24H ERROR IN REBOX : CORNER,I3,
           .        9H OF BLOCK,I4,20H NOT IN ADJACENT BOX)
      C
            END
```

```
      SUBROUTINE UPDAT
C
C------------------- UPDATE ALL CONTACTS ---
C
      COMMON A(3000)
      DIMENSION IA(1)
      EQUIVALENCE (A,IA)
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
     .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
     .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
     .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
     .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
      LOGICAL RFLAG,UFLAG,EFLAG
C
      LOGICAL FIRST
      DATA TOL,TOLB / 1.0 ,-0.01/
C
C------------------- SCAN EACH BLOCK ---
      DO 500 NB=1,NBLOKS
      I2=IA(NB)
      NC=IA(I2+1)
C------------------- SCAN EACH EDGE OF BLOCK ---
      IEND2=I2+20
      DO 400 NP=1,NC
      FIRST=.TRUE.
      IEND1=IEND2
      IEND2=IEND1+3
      IF(NP.EQ.NC) IEND2=I2+20
C------------------- DETERMINE BOXES TO BE SEARCHED ---
      X1=GLX(A(I2),IEND1)
      X2=GLX(A(I2),IEND2)
      Y1=GLY(A(I2),IEND1)
      Y2=GLY(A(I2),IEND2)
      TEMP=AMAX1(X1,X2)
      X1=AMIN1(X1,X2)
      X2=TEMP
      TEMP=AMAX1(Y1,Y2)
      Y1=AMIN1(Y1,Y2)
      Y2=TEMP
      NXL=IFIX((X1-TOL)/BSIZE)+1
      NXU=MIN0(IFIX((X2+TOL)/BSIZE)+1,IBOXES)
      NYL=IFIX((Y1-TOL)/BSIZE)+1
      NYU=MIN0(IFIX((Y2+TOL)/BSIZE)+1,JBOXES)
C------------------- SEARCH EACH CANDIDATE BOX ---
      DO 350 JBOX=NYL,NYU
      NBOX=(JBOX-1)*IBOXES+NXL-1
      DO 300 IBOX=NXL,NXU
      NBOX=NBOX+1
      I4=IA(M3+NBOX-1)
C------------------- END OF BOX LIST ? ---
  210 CONTINUE
      IF(I4.EQ.0) GOTO 300
C------------------- NO, IS THIS BLOCK NB ? ---
      IF(IA(I4+1).NE.NB) GOTO 220
```

```
FORTRAN IV-PLUS V02-51          17:07:09     16-FEB-78            PAGE 24
RBM.LST          /I4/TR:BLOCKS/WR

        C------------------- YES ---
        C------------------- GET NEXT ENTRY IN THIS BOX ---
0040      215 I4=IA(I4+2)
              GOTO 210
0041
        C------------------- FIRST TIME THROUGH ? ---
0042      220 IF(.NOT.FIRST) GOTO 230
        C------------------- YES, COMPUTE COS AND SIN FOR THIS EDGE ---
0043          FIRST=.FALSE.
0044          COSA=(GLX(A(I2),IEND2)-GLX(A(I2),IEND1))/A(IEND1+2)
0045          SINA=(GLY(A(I2),IEND2)-GLY(A(I2),IEND1))/A(IEND1+2)
        C------------------- COMPUTE CORNER COORDINATES RELATIVE TO EDGE ---
0046      230 I2C=IA(I4+1)
0047          I2C=IA(I2C)
0048          IC=I2C+IA(I4)*3+17
0049          YT=(GLY(A(I2C),IC)-GLY(A(I2),IEND1))*COSA
             .  -(GLX(A(I2C),IC)-GLX(A(I2),IEND1))*SINA
0050          IF(YT.GT.1.0) GOTO 215
0051          IF(YT.LE.-3.0) GOTO 215
0052          XT=(GLX(A(I2C),IC)-GLX(A(I2),IEND1))*COSA
             .  +(GLY(A(I2C),IC)-GLY(A(I2),IEND1))*SINA
0053          IF(XT.GT.A(IEND1+2)) GOTO 215
0054          IF(XT.LT.0.0) GOTO 215
        C------------------- CONTACT LIST FOR BLOCK NB ---
0055          J6=M5+NB-1
0056          I6=IA(J6)
        C------------------- END OF LIST ? ---
0057      235 CONTINUE
0058          IF(I6.EQ.0) GOTO 250
        C------------------- NO. SAME CORNER AND EDGE ? ---
0059          IF(IA(I4).EQ.IA(I6+2).AND.IA(I4+1).EQ.IA(I6+3)
             .   .AND.NP.EQ.IA(I6+1)) GOTO 240
        C------------------- NO. GET NEXT ENTRY IN CONTACT LIST ---
0060          J6=I6+4
0061          I6=IA(J6)
0062          GOTO 235
        C------------------- CONTACT ALREADY STORED ---
0063      240 IF(YT.GT.-2.0) GOTO 245
        C------------------- APPLY DRIFT CORRECTION ---
0064          WRITE(6,3000)
        C------------------- UPDATE CONTACT DATA ---
0065      245 A(I6+9)=SINA
0066          A(I6+10)=COSA
0067          A(I6+11)=GLX(A(I2C),IC)
0068          A(I6+12)=GLY(A(I2C),IC)
0069          IA(I6)=1
0070          GOTO 215
        C------------------- NEW CONTACT ? ---
0071      250 CONTINUE
0072          IF(YT.GT.0.0) GOTO 215
        C------------------- YES ---
0073          I6=NEMPT
0074          ICR=IC-3
0075          IF(IA(I4).EQ.1) ICR=IC+3*(IA(I2C+1)-1)
0076          YTR=(GLY(A(I2C),ICR)-GLY(A(I2),IEND1))*COSA
             .   -(GLX(A(I2C),ICR)-GLX(A(I2),IEND1))*SINA
0077          IF(YTR.LE.-2.0) GOTO 215
```

```
FORTRAN IV-PLUS V02-51          17:07:09    16-FEB-78            PAGE 25
RBM.LST          /I4/TR:BLOCKS/WR

            ICL=IC+3
            IF(IA(I4).EQ.IA(I2C+1)) ICL=I2C+20
            YTL=(GLY(A(I2C),ICL)-GLY(A(I2),IEND1))*COSA
     .         -(GLX(A(I2C),ICL)-GLX(A(I2),IEND1))*SINA
            IF(YTL.LE.-2.0) GOTO 215
      C------------------- ANY SPACE AVAILABLE IN EMPTY LIST ? ---
            IF(IA(NEMPT+4).NE.0) GOTO 260
            WRITE(6,3001)
            CALL FINISH
      C------------------- NEW CONTACT ---
        260 A(I6+5)=0.0
            A(I6+6)=0.0
            A(I6+7)=0.0
            A(I6+8)=0.0
            IA(I6+1)=NP
            IA(I6+2)=IA(I4)
            IA(I6+3)=IA(I4+1)
            NEMPT=IA(I6+4)
            IA(J6)=I6
            IA(I6+4)=0
            GOTO 245
      C------------------- END OF BOX SCAN ---
        300 CONTINUE
        350 CONTINUE
      C------------------- END OF EDGE SCAN ---
        400 CONTINUE
      C------------------- SCAN CONTACT LIST FOR PRESERVE FLAGS ---
            J6=M5+NB-1
            I6=IA(J6)
      C------------------- END OF LIST ? ---
        410 IF(I6.EQ.0) GOTO 490
      C------------------- NO ---
      C------------------- IS THE PRESERVE FLAG SET ? ---
            IF(IA(I6).EQ.0) GOTO 420
      C------------------- YES ---
            IA(I6)=0
            J6=I6+4
            GOTO 430
      C------------------- NO ---
        420 IA(J6)=IA(I6+4)
            IA(I6+4)=NEMPT
            NEMPT=I6
      C------------------- GET NEXT CONTACT ---
        430 I6=IA(J6)
            GOTO 410
      C------------------- END OF BLOCK SCAN ---
        490 CONTINUE
        500 CONTINUE
      C
            NUPDAT=NUPDAT+1
            UFLAG=.FALSE.
            UMOST=0.0
            RETURN
      C
       3000 FORMAT(30X,26H DRIFT CORRECTION REQUIRED)
       3001 FORMAT(30X,32H NO MORE MEMORY FOR CONTACT LIST)
```

```
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RBM.LST          /I4/TR:BLOCKS/WR

        C
0119          END
```

```
0001          FUNCTION GLX(B,IC)
       C
       C-------------------- LOCAL-GLOBAL X-COORDINATE TRANSFORMATION ---
       C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          DIMENSION B(1)
       C
0006          GLX=B(3)+A(IC)*B(19)-A(IC+1)*B(20)
       C
0007          RETURN
       C
0008          END
```

```
FORTRAN IV-PLUS V02-51          17:08:33    16-FEB-78           PAGE 30
RBM.LST          /I4/TR:BLOCKS/WR


0001            FUNCTION GLY(B,IC)
          C
          C------------------- LOCAL-GLOBAL Y-COORDINATE TRANSFORMATION ---
          C
0002            COMMON A(3000)
0003            DIMENSION IA(1)
0004            EQUIVALENCE (A,IA)
0005            DIMENSION B(1)
          C
0006            GLY=B(4)+A(IC)*B(20)+A(IC+1)*B(19)
          C
0007            RETURN
          C
0008            END
```

```
      SUBROUTINE DUMP
C
C------------------- ROUTINE TO PRINT MEMORY ALLOCATION AND CONTENTS
C
      COMMON A(3000)
      DIMENSION IA(1)
      EQUIVALENCE (A,IA)
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
     .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
     .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
     .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
     .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
      LOGICAL RFLAG,UFLAG,EFLAG
C
      IF(LOC2.EQ.0) RETURN
      WRITE(6,2000)
      WRITE(6,2005) M1,M2,M3,M4,M5,M6,M7,NBLOKS,NCYC,NEMPT,MCYCLE
      IF(LOC2.LT.0) GOTO 100
C------------------- DUMP CONSECUTIVE MEMORY LOCATIONS ---
      WRITE(6,2009)
      I2=((LOC1-1)/10)*10
   10 I1=I2+1
      I2=I1+9
      WRITE(6,2001) (IA(I),I=I1,I2),I2
      IF(I2.LT.LOC2) GOTO 10
      GOTO 500
C
C------------------- DUMP BY BOX ---
  100 WRITE(6,2002)
      DO 120 NBOX=1,NBOXES
      I3=IA(M3+NBOX-1)
C------------------- ANY MORE ENTRIES ? ---
  110 IF(I3.EQ.0) GOTO 120
C------------------- NO, PRINT BLOCK,CORNER ---
      WRITE(6,2008) NBOX,IA(I3+1),IA(I3)
      I3=IA(I3+2)
      GOTO 110
  120 CONTINUE
C------------------- CONTENTS OF EACH BLOCK ---
      WRITE(6,2006)
      DO 130 NB=1,NBLOKS
      IF=IA(NB)
      IL=IF+19+3*IA(IF+1)
      WRITE(6,2003) NB,IA(IF),IA(IF+1),(A(I),I=IF+2,IL)
  130 CONTINUE
C------------------- DUMP CONTACT DATA ---
      IF(M5.EQ.0) GOTO 500
      WRITE(6,2007)
      DO 150 NB=1,NBLOKS
      J6=M5+NB-1
  140 I6=IA(J6)
      IF(I6.EQ.0) GOTO 150
      WRITE(6,2004) NB,(IA(I),I=I6,I6+4),
     .              (A(I),I=I6+5,I6+12)
```

```
              J6=I6+4
              GOTO 140
      150 CONTINUE
C------------------
      500 WRITE(6,2000)
C
              RETURN
C
     2000 FORMAT(1X,130(1H-))
     2001 FORMAT(1X,10O12,I6)
     2002 FORMAT(10X,3HBOX,7X,5HBLOCK,6X,6HCORNER)
     2003 FORMAT(/1X,3I3,1P11E10.2/(10X,1P11E10.2))
     2004 FORMAT(/1X,6I10/1X,1P8E10.2)
     2005 FORMAT(9X,2HM1,8X,2HM2,8X,2HM3,8X,2HM4,8X,2HM5,8X,2HM6,
         .       8X,2HM7,4X,6HNBLOKS,6X,4HNCYC,5X,5HNEMPT,4X,6HMCYCLE/
         .       1X,11I10)
     2006 FORMAT(11H BLOCK DATA,10(1H-)/1X,9H NB IF NC,8X,2HXC,8X,2HYC,
         .       5X,5HTHETA,6X,4HXDOT,6X,4HYDOT,6X,4HTDOT,
         .       8X,2HDX,8X,2HDY,4X,6HDTHETA,6X,4HAREA,3X,7HINERTIA/
         .       15X,5HXFSUM,5X,5HYFSUM,6X,4HMSUM,5X,5HXLOAD,5X,5HYLOAD,
         .       7X,3HCOS,7X,3HSIN)
     2007 FORMAT(13H CONTACT DATA,10(1H-)/8X,3HNBE,7X,3HPRE,7X,3HNPE,7X,
         .       3HNPC,7X,3HNBC,6X,4HLINK/10X,1HS,9X,1HN,8X,2HFN,8X,2HFS,
         .       7X,3HSIN,7X,3HCOS,7X,3HXCP,7X,3HYCP)
     2008 FORMAT(1X,3I12)
     2009 FORMAT(1X,30(1H*),19HVALUES ARE IN OCTAL,30(1H*))
C
              END
```

```
0001            SUBROUTINE BPLOT
          C
          C------------------- PLOT A SNAPSHOT OF THE GEOMETRY ---
          C
0002            COMMON A(3000)
0003            DIMENSION IA(1)
0004            EQUIVALENCE (A,IA)
0005            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
               .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
               .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
               .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
               .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
               .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006            LOGICAL RFLAG,UFLAG,EFLAG
          C
0007            SCREEN=10.0
0008            FACT=SCREEN/AMAX1(XSIZE,YSIZE)
          C------------------- PLOT EACH BLOCK ---
0009            DO 100 NB=1,NBLOKS
0010            I2=IA(NB)
0011            NC=IA(I2+1)
0012            XC=FACT*A(I2+2)
0013            YC=FACT*A(I2+3)
          C------------------- FIXED ? ---
0014            IF(IA(I2).EQ.0) GOTO 20
          C------------------- YES, ALREADY PLOTTED ? ---
0015            IF(IA(I2).GT.2) GOTO 100
          C------------------- NO ---
0016            IA(I2)=IA(I2)+2
0017            CALL SYMBOL(XC,YC,0.2,1HF,0.0,1)
0018         20 IC=I2+20
0019            X=FACT*GLX(A(I2),IC)
0020            Y=FACT*GLY(A(I2),IC)
0021            CALL PLOT(X,Y,3)
0022            DO 50 NP=2,NC
0023            IC=IC+3
0024            X=FACT*GLX(A(I2),IC)
0025            Y=FACT*GLY(A(I2),IC)
0026            CALL PLOT(X,Y,2)
0027         50 CONTINUE
0028            X=FACT*GLX(A(I2),I2+20)
0029            Y=FACT*GLY(A(I2),I2+20)
0030            CALL PLOT(X,Y,2)
          C------------------- END OF BLOCK LOOP ---
0031        100 CONTINUE
          C
0032            CALL PLOT(X,Y,3)
0033            CALL PLOT(0.0,0.0,3)
          C
0034            RETURN
          C
0035            END
```

```
FORTRAN IV-PLUS V02-51          17:09:04    16-FEB-78           PAGE 37
RBM.LST          /I4/TR:BLOCKS/WR


0001            SUBROUTINE FINISH
          C
          C------------------- TIDY UP AND STOP ---
          C
0002            COMMON A(3000)
0003            DIMENSION IA(1)
0004            EQUIVALENCE (A,IA)
0005            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
           .                    NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
           .                    TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
           .                    UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
           .                    CON1,CON2,NVARB,NFRAG,NBR,NPR,
           .                    GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006            LOGICAL RFLAG,UFLAG,EFLAG
          C
0007            CALL PLOTND
0008            WRITE(6,2000) MCYCLE,NUPDAT
          C
          C------------------- WRITE RESTART FILE IF NO ERRORS ---
0009            IF(EFLAG) GOTO 100
0010            REWIND 1
0011            WRITE(1) (HED(I),I=1,LBLOCK)
0012            WRITE(1) (A(I),I=1,M7)
0013            WRITE(6,2001)
0014        100 STOP
          C
0015       2000 FORMAT(30X,13H TOTAL CYCLES,I10/
           .           30X,13H NO. UPDATES ,I10)
0016       2001 FORMAT(30X,32H A RESTART FILE HAS BEEN WRITTEN)
          C
0017            END
```

```
FORTRAN IV-PLUS V02-51            17:09:09     16-FEB-78            PAGE 39
RBM.LST          /14/TR:BLOCKS/WR

0001          SUBROUTINE CHECK
        C
        C------------------- MOMENTUM AND ENERGY CHECK ---
        C
0002          COMMON A(3000)
0003          DIMENSION IA(1)
0004          EQUIVALENCE (A,IA)
0005          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,
             .                TFRAC,TDEL,IBOXES,JBOXES,BSIZE,XSIZE,YSIZE,
             .                UDMAX,UMOST,STIFN,STIFS,FRIC,ALPHA,BETA,BDT,
             .                CON1,CON2,NVARB,NFRAG,NBR,NPR,
             .                GRAVX,GRAVY,LOC1,LOC2,NUPDAT,LBLOCK
0006          LOGICAL RFLAG,UFLAG,EFLAG
        C
0007          XMOM=0.0
0008          YMOM=0.0
0009          TMOM=0.0
0010          TARM=0.0
0011          XKE=0.0
0012          YKE=0.0
0013          TKE=0.0
0014          DO 100 NB=1,NBLOKS
0015          I2=IA(NB)
0016          XMOM=XMOM+A(I2+11)*A(I2+5)
0017          YMOM=YMOM+A(I2+11)*A(I2+6)
0018          TMOM=TMOM+A(I2+12)*A(I2+7)
0019          TARM=TARM+A(I2+11)*(A(I2+2)*A(I2+6)-A(I2+3)*A(I2+5))
0020          XKE=XKE+0.5*A(I2+11)*A(I2+5)**2
0021          YKE=YKE+0.5*A(I2+11)*A(I2+6)**2
0022          TKE=TKE+0.5*A(I2+12)*A(I2+7)**2
0023          WRITE(6,2001) XMOM,YMOM,TMOM,TARM,XKE,YKE,TKE
0024      100 CONTINUE
        C
0025          ESUM=XKE+YKE+TKE
0026          TSUM=TMOM+TARM
        C
0027          WRITE(6,2000) XMOM,YMOM,TMOM,TARM,TSUM,XKE,YKE,TKE,ESUM
        C
0028          RETURN
        C
0029     2000 FORMAT(9H MOMENTUM,11X,1HX,11X,1HY,2X,10HROTATIONAL/
             .       9X,1P5E12.4//
             .       9H ENERGY  ,11X,1HX,11X,1HY,2X,10HROTATIONAL,7X,5HTOTAL/
             .       9X,1P4E12.4)
0030     2001 FORMAT(1X,1P7E12.4)
        C
0031          END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1  000712    229              RW,I,CON,LCL
```

APPENDIX XIII: LISTING OF PROGRAM SDEM

```
FORTRAN IV-PLUS V02-04G         17:35:23    22-MAR-78          PAGE 1
RBM.FTN          /I4/TR:BLOCKS/WR

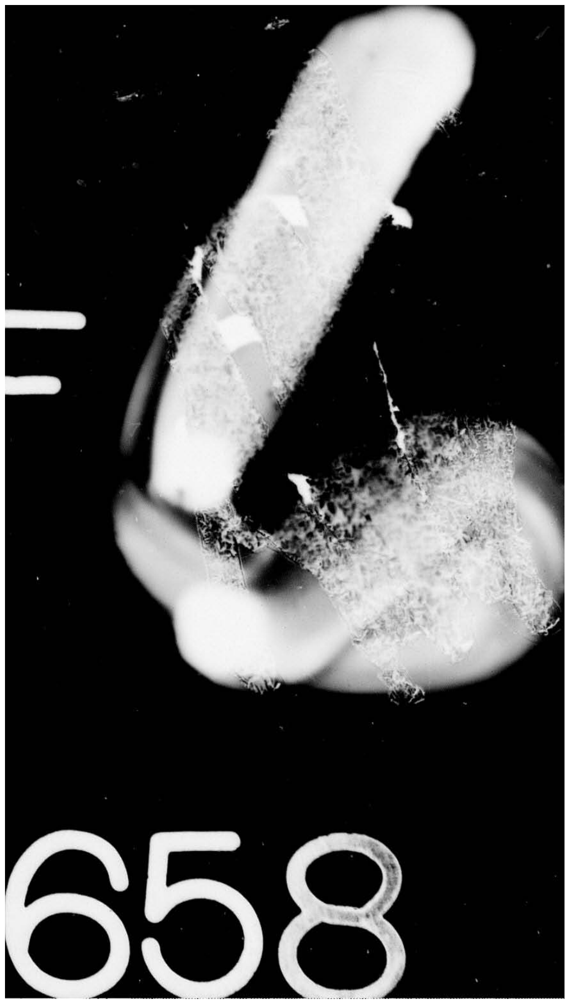
0001             PROGRAM SDEM
           C
           C-----------------------------------------------------------
           C------------------- RIGID BLOCK MODEL. ---------------------
           C------------------- FREELY TRANSLATED INTO FORTRAN BY -------
           C------------------- P.J.BERESFORD, FROM AN ORIGINAL PROGRAM -
           C------------------- BY P.A.CUNDALL. ------------------------
           C------------------- DAMES AND MOORE, LONDON. ----------------
           C------------------- VERSION 2.0, NOVEMBER 1977. --------------
           C------------------- MODIFIED BY P.A. CUNDALL TO --------------
           C------------------- INCLUDE LIMITED DEFORMABILITY ------------
           C-----------------------------------------------------------
           C
0002             INCLUDE 'COMMON.FTN'
0003 *           COMMON A(5000)
0004 *           DIMENSION IA(1)
0005 *           EQUIVALENCE (A,IA)
0006             INCLUDE 'CBLOCK.FTN'
0007 *           LOGICAL LOCK
0008 *           LOGICAL RFLAG,UFLAG,EFLAG
0009 *           REAL LAME1,LAME2
0010 *           COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *         .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *         .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *         .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *         .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *         .                LOCK,LBLOCK
           C
0011             DATA STIFN,STIFS,FRIC,BETA/2*1.0E8,0.0,0.0/
0012             DATA YIELD /1.0E10/
0013             DATA GRAVY,GRAVX/-9.81,0.0/
0014             DATA M7,MCYCLE,NUPDAT,LBLOCK/3000,0,0,75/
0015             DATA RFLAG,UFLAG,EFLAG/.FALSE.,.TRUE.,.FALSE./
0016             DATA LOCK /.FALSE./
0017             DATA NVARB /24/
           C
0018             CALL PLOTST(.025,'CM')
0019             CALL SETUP
0020          10 CALL NEXT
0021             CALL CYCLE
0022             GOTO 10
           C
0023             END
```

```
FORTRAN IV-PLUS V02-04G          17:35:38     22-MAR-78            PAGE 1
SETUP.FTN        /14/TR:BLOCKS/WR

0001             SUBROUTINE SETUP
           C
0002             INCLUDE 'COMMON.FTN'
0003 *           COMMON A(5000)
0004 *           DIMENSION IA(1)
0005 *           EQUIVALENCE (A,IA)
0006             INCLUDE 'CBLOCK.FTN'
0007 *           LOGICAL LOCK
0008 *           LOGICAL RFLAG,UFLAG,EFLAG
0009 *           REAL LAME1,LAME2
0010 *           COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *         .                 NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *         .                 TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *         .                 CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *         .                 G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *         .                 LOCK,LBLOCK
           C
0011             DIMENSION CARD(20),WORD(10)
0012             BYTE DAY(10),TIM(10)
           C
0013             DATA WORD /4HSTAR,4HREST,4HBLOC,4HBOXE,4HXLIM,
                .           4HYLIM,4H****,4HFRAC,4HZZZZ,4HZZZZ/
           C
0014             JOB=0
0015             CALL DATE(DAY)
0016             CALL TIME(TIM)
0017             WRITE(6,2000) DAY,TIM
           C------------------- READ NEXT CARD ---
0018          10 READ(5,1000) CARD
0019             CALL TIME(TIM)
0020             WRITE(6,2001) CARD,TIM
           C
0021             DO 20 I=1,10
0022             IF(CARD(1).EQ.WORD(I)) GOTO 30
0023          20 CONTINUE
           C
0024             WRITE(6,3000)
0025             GOTO 10
           C
0026          30 IF(I.GT.2.AND.JOB.EQ.0) GOTO 60
0027             GOTO (110,120,130,140,150,
                .      160,900,170, 10, 10), I
           C
0028          50 WRITE(6,3001)
0029             GOTO 10
           C
0030          60 WRITE(6,3002)
0031             GOTO 10
           C------------------- START OF NEW RUN ---
0032         110 JOB=1
0033             DO 111 I=1,20
0034         111 HED(I)=CARD(I)
0035             GOTO 10
           C------------------- RESTART RUN ---
0036         120 JOB=2
```

AD-A061 658 DAMES AND MOORE LOS ANGELES CA F/G 8/7
COMPUTER MODELING OF JOINTED ROCK MASSES.(U)
AUG 78 T MAINI, P CUNDALL, J MARTI DACA39-77-C-0004
UNCLASSIFIED WES-TR-N-78-4 NL

4 OF 6
AD
A061 658


658

```
      READ(1) (HED(I),I=1,LBLOCK)
      READ(1) (A(I),I=1,M7)
      WRITE(6,2003) MCYCLE
      WRITE(6,2004) HED
      RETURN
C------------------- MAXIMUM NUMBER OF BLOCKS ---
  130 DECODE(20,1001,CARD) NBLOKM
      GOTO 10
C------------------- NUMBER OF BOXES ---
  140 DECODE(40,1001,CARD) IBOXES,JBOXES,IBSIZE
      BSIZE=FLOAT(IBSIZE)
      NBOXES=IBOXES*JBOXES
      GOTO 10
C------------------- PROBLEM X-LIMITS ---
  150 DECODE(30,1002,CARD) XL,XU
      IF(XL.LT.XU) GOTO 10
      TEMP=XL
      XL=XU
      XU=TEMP
      GOTO 10
C------------------- PROBLEM Y-LIMITS ---
  160 DECODE(30,1002,CARD) YL,YU
      IF(YL.LT.YU) GOTO 10
      TEMP=YL
      YL=YU
      YU=TEMP
      GOTO 10
C------------------- FRACTION OF CRITICAL TIMESTEP ---
  170 DECODE(20,1002,CARD) TFRAC
      GOTO 10
C------------------- SETUP FINISHED ---
  900 CONTINUE
C------------------- INITIALISE SOME VARIABLES ---
      UMOST=0.0
      NBLOKS=0
      XSIZE=FLOAT(IBOXES)*BSIZE
      YSIZE=FLOAT(JBOXES)*BSIZE
      XF=XSIZE/(XU-XL)
      YF=YSIZE/(YU-YL)
      SFACT=AMIN1(XF,YF)
      M1=1
      M2=M1+NBLOKM
      M3=M2
      WRITE(6,2002) NBLOKM,NBOXES,XL,XU,YL,YU,BSIZE,SFACT
      RETURN
C
 1000 FORMAT(20A4)
 1001 FORMAT(10X,3I10)
 1002 FORMAT(10X,5F10.0)
 2000 FORMAT(30X28HSDEM - SIMPLY-DEFORMABLE DEM,53X,10A1,1X,10A1/
     .       30X28H----------------------------/)
 2001 FORMAT(1X,4H+++ ,20A4,4H +++,32X,10A1)
 2002 FORMAT(/30X,25H MAXIMUM NUMBER OF BLOCKS,I5/
     .        30X,25H NUMBER OF BOXES         ,I5/
     .        30X,10H X-LIMITS ,2F10.2/
     .        30X,10H Y-LIMITS ,2F10.2/
```

```
FORTRAN IV-PLUS V02-04G         17:35:38     22-MAR-78            PAGE 3
SETUP.FTN        /I4/TR:BLOCKS/WR

                .        30X,10H BSIZE     ,F10.2/
                .        30X,10H SFACT     ,F10.2)
0081       2003 FORMAT(30X,31H RESTART RUN. CURRENT CYCLES ...,I10)
0082       2004 FORMAT(30X,9HHEADING: ,20A4)
0083       3000 FORMAT(28H !!! ERROR : ILLEGAL COMMAND)
0084       3001 FORMAT(34H !!! ERROR : COMMAND NOT AVAILABLE)
0085       3002 FORMAT(48H !!! ERROR : 'START' OR 'RESTART' CARD NOT FOUND)
          C
0086            END

PROGRAM SECTIONS

 NAME        SIZE                       ATTRIBUTES

$CODE1  002220   584                    RW,I,CON,LCL
$PDATA  000026    11                    RW,D,CON,LCL
$IDATA  000740   240                    RW,D,CON,LCL
$VARS   000244    82                    RW,D,CON,LCL
$TEMPS  000004     2                    RW,D,CON,LCL
.$$$$.  047040 10000                    RW,D,OVR,GBL
CBLOCK  000460   152                    RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 053176 11071

SETUP,0=SETUP
```

```
FORTRAN IV-PLUS V02-04G          17:36:23    22-MAR-78            PAGE 1
NEXT.FTN          /14/TR:BLOCKS/WR

0001            SUBROUTINE NEXT
          C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(5000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          LOGICAL LOCK
0008 *          LOGICAL RFLAG,UFLAG,EFLAG
0009 *          REAL LAME1,LAME2
0010 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *         .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *         .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *         .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *         .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *         .                LOCK,LBLOCK
          C
0011            COMMON /PAR/ LINE(80),RVAR(10),IVAR(10),AVAR(10)
0012            DIMENSION CARD(20),WORD(20),X(50),Y(50),ICODE(20)
0013            BYTE TIM(10)
          C
0014            DATA WORD /4HCREA,4HDELE,4HDUMP,4HCYCL,4HSTOP,
               .          4HPLOT,4H****,4HRSET,4HISET,4HCHEC,
               .          4HGRAV,4HSTIF,4HDAMP,4HFRIC,4HZERO,
               .          4HLOAD,4HBDAM,4HELAS,4HLOCK,4HPLAS/
0015            DATA ICODE /
               .     0000000121,0000000000,0000000011,0000000001,0000000000,
               .     0000000000,0000000000,0000000021,0000000011,0000000000,
               .     0000000022,0000000022,0000001122,0000000002,0000000000,
               .     0000000122,0000000022,0000000022,0000000003,0000000022/
          C
          C------------------- READ NEXT CARD ---
0016         10 READ(5,1000) CARD
0017            CALL TIME(TIM)
0018            WRITE(6,2000) CARD,TIM
0019            DO 20 I=1,20
0020            IF(CARD(1).EQ.WORD(I)) GOTO 30
0021         20 CONTINUE
0022            WRITE(6,3000)
0023            GOTO 10
0024         30 DECODE(80,1007,CARD) LINE
0025            CALL PARSE(ICODE(I),IERR)
0026            IF(IERR.EQ.0) GOTO 35
0027            CALL FINISH
          C------------------- JUMP TO APPROPRIATE CODE ---
0028         35 GOTO (100,150,200,250,300,
               .       350,400,450,500,550,
               .       600,650,700,750,800,
               .       850,900,950,970,980), I
          C
0029         40 WRITE(6,3001)
0030            GOTO 10
          C------------------- CREATE A NEW BLOCK ---
0031        100 NBLOKS=NBLOKS+1
0032            NC=IVAR(1)
```

```
FORTRAN IV-PLUS V02-04G          17:36:23     22-MAR-78              PAGE 2
NEXT.FTN          /14/TR:BLOCKS/WR

      RHO=RVAR(2)
      READ(5,1002) (X(I),Y(I),I=1,NC)
      WRITE(6,2001) (X(I),Y(I),I=1,NC)
      I2=M3
      IA(NBLOKS)=I2
      IF(IVAR(3).NE.0) IA(I2)=1
      IA(I2+1)=NC
C------------------- AREA AND CENTROID OF THIS BLOCK ---
      AREA=(X(1)-X(NC))*(Y(1)+Y(NC))
      YC=(X(1)-X(NC))*((Y(1)-Y(NC))*(Y(1)+2.0*Y(NC))+3.0*Y(NC)**2)
      XC=(Y(1)-Y(NC))*((X(1)-X(NC))*(X(1)+2.0*X(NC))+3.0*X(NC)**2)
      DO 110 I=2,NC
      AREA=AREA+(X(I)-X(I-1))*(Y(I)+Y(I-1))
      YC=YC+(X(I)-X(I-1))*((Y(I)-Y(I-1))*(Y(I)+2.0*Y(I-1))
     .      +3.0*Y(I-1)**2)
      XC=XC+(Y(I)-Y(I-1))*((X(I)-X(I-1))*(X(I)+2.0*X(I-1))
     .      +3.0*X(I-1)**2)
  110 CONTINUE
      AREA=0.5*AREA
      YC=YC/(6.0*AREA)
      XC=-XC/(6.0*AREA)
      YC=(YC-YL)*SFACT
      XC=(XC-XL)*SFACT
      AREA=AREA*SFACT*SFACT
      A(I2+2)=XC
      A(I2+3)=YC
      A(I2+7)=AREA*RHO
C------------------- LOCAL COORDINATES FOR THIS BLOCK ---
      M3=M3+NVARB
      A(M3)=(X(1)-XL)*SFACT-XC
      A(M3+1)=(Y(1)-YL)*SFACT-YC
      DO 120 I=2,NC
      A(M3+3)=(X(I)-XL)*SFACT-XC
      A(M3+4)=(Y(I)-YL)*SFACT-YC
      A(M3+2)=SQRT((A(M3+3)-A(M3))**2+(A(M3+4)-A(M3+1))**2)
  120 M3=M3+3
      A(M3+2)=SQRT((A(I2+NVARB)-A(M3))**2+(A(I2+NVARB+1)-A(M3+1))**2)
      M3=M3+3
C------------------- MOMENT OF INERTIA ---
      RMOI=0.0
      IC=I2+NVARB
      DO 130 NP=2,NC
      AREA=A(IC)*A(IC+1) + (A(IC+3)-A(IC))*(A(IC+4)+A(IC+1))
     .      - A(IC+3)*A(IC+4)
      AREA=0.5*AREA
      TEMP=A(IC)**2+A(IC+1)**2+A(IC+3)**2+A(IC+4)**2
     .      +A(IC)*A(IC+3)+A(IC+1)*A(IC+4)
      RMOI=RMOI+AREA*TEMP/6.0
  130 IC=IC+3
      AREA=A(IC)*A(IC+1)+(A(I2+NVARB)-A(IC))*(A(I2+NVARB+1)+A(IC+1))
     .      - A(I2+NVARB)*A(I2+NVARB+1)
      AREA=0.5*AREA
      TEMP=A(I2+NVARB)**2+A(I2+NVARB+1)**2+A(IC)**2+A(IC+1)**2
     .      +A(I2+NVARB)*A(IC)+A(I2+NVARB+1)*A(IC+1)
      RMOI=RMOI+AREA*TEMP/6.0
      A(I2+8)=RMOI*RHO
```

```
         C
         C------------------- BACK TO GLOBAL CO-ORDINATES ---
0080           IC=I2+NVARB
0081           DO 140 NP=1,NC
0082           A(IC)=A(IC)+A(I2+2)
0083           A(IC+1)=A(IC+1)+A(I2+3)
0084       140 IC=IC+3
0085           WRITE(6,2002) XC,YC,A(I2+7),A(I2+8)
0086           GOTO 10
         C------------------- DELETE A BLOCK ---
0087       150 GOTO 40
         C------------------- DUMP MEMORY AS REQUESTED ---
0088       200 LOC1=IVAR(1)
0089           LOC2=IVAR(2)
0090           IF(LOC2.NE.0) GOTO 220
0091           LOC2=LOC1
0092           LOC1=1
0093       220 CALL DUMP
0094           GOTO 10
         C------------------- CYCLE ROUND MOTION AND FORD ---
0095       250 NCYC=IVAR(1)
0096           IF(MCYCLE.EQ.0) CALL BOX
0097           RETURN
         C------------------- STOP COMMAND ---
0098       300 CALL FINISH
         C------------------- PLOT COMMAND ---
0099       350 CALL BPLOT
0100           GOTO 10
         C------------------- RETURN TO PHASE 1 ---
0101       400 CALL SETUP
0102           GOTO 10
         C------------------- SET REAL DATA ---
0103       450 IADR=IVAR(1)
0104           IF(IADR.LE.0.OR.IADR.GT.M7) GOTO 480
0105           A(IADR)=RVAR(2)
0106           GOTO 10
0107       480 WRITE(6,3002)
0108           GOTO 10
         C------------------- SET INTEGER DATA ---
0109       500 IADR=IVAR(1)
0110           IF(IADR.LE.0.OR.IADR.GT.M7) GOTO 480
0111           IA(IADR)=IVAR(2)
0112           GOTO 10
         C------------------- MOMENTUM & ENERGY CHECK ---
0113       550 CALL CHECK
0114           GOTO 10
         C------------------- GRAVITY ---
0115       600 GRAVY=RVAR(1)
0116           GRAVX=RVAR(2)
0117           GOTO 10
         C------------------- CONTACT STIFFNESSES ---
0118       650 STIFN=RVAR(1)
0119           STIFS=RVAR(2)
0120           GOTO 10
         C------------------- RAYLEIGH DAMPING ---
0121       700 PI2=8.0*ATAN(1.0)
```

```
FORTRAN IV-PLUS V02-04G         17:36:23    22-MAR-78           PAGE 4
NEXT.FTN          /I4/TR:BLOCKS/WR

            ALPHA=PI2*RVAR(1)*RVAR(2)
            BETA=RVAR(1)/(PI2*RVAR(2))
            IF(IVAR(3).EQ.0) GO TO 710
            ALPHA=0.0
            WRITE(6,3003)
        710 IF(IVAR(4).EQ.0) GO TO 720
            BETA=0.0
            WRITE(6,3004)
        720 IF(MCYCLE.EQ.0) GO TO 10
            BDT=BETA/TDEL
            CON1=1.0-ALPHA*TDEL/2.0
            CON2=1.0/(1.0+ALPHA*TDEL/2.0)
            GOTO 10
      C------------------- FRICTION COEFFICIENT ---
        750 FRIC=RVAR(1)
            GOTO 10
      C------------------- ZERO ALL VELOCITIES ---
        800 DO 820 NB=1,NBLOKS
            I2=IA(NB)
            A(I2+5)=0.0
            A(I2+6)=0.0
            A(I2+7)=0.0
        820 CONTINUE
            GOTO 10
      C------------------- SET BLOCK LOADS ---
        850 NB=IVAR(3)
            I2=IA(NB)
            A(I2+16)=RVAR(1)
            A(I2+17)=RVAR(2)
            GOTO 10
      C------------------- INTERNAL BLOCK DAMPING ---
        900 PI2=8.0*ATAN(1.0)
            ALPHB=PI2*RVAR(1)*RVAR(2)
            IF(MCYCLE.EQ.0) GOTO 10
            CON1B=1.0-ALPHB*TDEL/2.0
            CON2B=1.0/(1.0+ALPHB*TDEL/2.0)
            GOTO 10
      C------------------- ELASTIC PROPERTIES FOR BLOCKS ---
        950 G=RVAR(2)
            LAME1=RVAR(1)+4.0*G/3.0
            LAME2=RVAR(1)-2.0*G/3.0
            GOTO 10
      C------------------- LOCKED OR UNLOCKED JOINTS ---
        970 LOCK=AVAR(1).EQ.4HON
            GOTO 10
      C------------------- PLASTICITY CONSTANTS ---
        980 YIELD=RVAR(1)
            GOTO 10
      C
       1000 FORMAT(20A4)
       1001 FORMAT(10X,I10,F10.0,I10)
       1002 FORMAT(8F10.0)
       1003 FORMAT(10X,2I10)
       1004 FORMAT(10X,I10,F10.0)
       1005 FORMAT(10X,2F10.0)
       1006 FORMAT(10X,2F10.0,2I10)
```

```
FORTRAN IV-PLUS V02-04G          17:36:23     22-MAR-78             PAGE 5
NEXT.FTN         /I4/TR:BLOCKS/WR

      1007 FORMAT(80A1)
      2000 FORMAT(1X,4H+++ ,20A4,4H +++,32X,10A1)
      2001 FORMAT(1X,4(1H(,E12.4,1H,,E12.4,3H ) ))
      2002 FORMAT(18H XC,YC,MASS,RHOI :,1P4E12.3)
      3000 FORMAT(28H !!! ERROR : ILLEGAL COMMAND)
      3001 FORMAT(34H !!! ERROR : COMMAND NOT AVAILABLE)
      3002 FORMAT(33H !!! ERROR : ADDRESS OUT OF RANGE)
      3003 FORMAT(10X,29HMASS DAMPING TERM SET TO ZERO)
      3004 FORMAT(10X,34HSTIFFNESS DAMPING TERM SET TO ZERO)
     C
           END

PROGRAM SECTIONS

 NAME        SIZE                 ATTRIBUTES

$CODE1   005472  1437             RW,I,CON,LCL
$PDATA   000056    23             RW,D,CON,LCL
$IDATA   000456   151             RW,D,CON,LCL
$VARS    001306   355             RW,D,CON,LCL
$TEMPS   000034    14             RW,D,CON,LCL
.$$$$.   047040 10000             RW,D,OVR,GBL
CBLOCK   000460   152             RW,D,OVR,GBL
PAR      000670   220             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 060200 12352

NEXT,0=NEXT
```

```
FORTRAN IV-PLUS V02-04G          17:37:47    22-MAR-78            PAGE 1
PARSE.FTN        /I4/TR:BLOCKS/WR

0001          SUBROUTINE PARSE(ICODE,IERR)
        C
        C   ROUTINE TO PARSE INPUT LINE ACCORDING TO EXPECTED NUMBER
        C   AND TYPE OF ARGUMENTS FOLLOWING A COMMAND WORD.
        C   THE COMMAND WORD IS DISCARDED (IT IS UP TO THE USER TO
        C   INTERPRET THE COMMAND WORD).
        C   WRITTEN BY P.A. CUNDALL, JULY 4, 1977.
        C   MODIFIED NOV 4, 1977 BY P.A. CUNDALL TO USE DECIMAL
        C   CODES INSTEAD OF OCTAL.
        C
        C   NOTES:  1)  ARGUMENTS CAN BE SEPARATED BY BLANKS OR COMMAS
        C   ------  2)  MULTIPLE CONTIGUOUS SEPARATORS ARE TREATED AS ONE
        C           3)  MAXIMUM NUMBER OF ARGUMENTS IS 10
        C           4)  LAST ARGUMENT MUST NOT BE ALPHANUMERIC
        C
        C   INPUT:  1) ICODE (32 BIT WORD). THIS IS PACKED WITH UP TO TEN
        C   ------      NUMBERS DENOTING THE EXPECTED FORM AND NUMBER
        C              OF ARGUMENTS. THE CODES ARE:
        C                                  0 = NOTHING
        C                                  1 = INTEGER
        C                                  2 = REAL
        C                                  3 = ALPHANUMERIC
        C              EXAMPLE: ICODE = 1321  MEANS -
        C              --------                         FIRST PARAMETER IS INTEGER
        C                                               SECOND IS REAL
        C                                               THIRD IS ALPHANUMERIC
        C                                               LAST IS INTEGER
        C           2) LINE(80) ... THIS IS THE INPUT LINE IN 80A1 FORMAT
        C
        C   OUTPUT: 1) RVAR(10),IVAR(10),AVAR(10)
        C   -------    THE INPUT PARAMETERS APPEAR IN THE APPROPRIATE ARRAY.
        C              FOR EXAMPLE, AN INTEGER VARIABLE AS THE THIRD PARAMETER
        C              WOULD TURN UP IN IVAR(3).
        C              UNUSED VARIABLES APPEAR AS ZERO OR BLANK
        C
        C           2) IERR = 4 INDICATES AN ERROR RETURN
        C
0002          COMMON /PAR/ LINE(80),RVAR(10),IVAR(10),AVAR(10)
0003          DIMENSION MLINE(20),LPOINT(20),WORD(5),LCODE(10)
        C
0004          DO 5 I=1,10
0005          RVAR(I)=0.0
0006          IVAR(I)=0
0007        5 AVAR(I)=4H
        C
0008          IERR=0
0009          NARG=0
0010          LMAX=80
0011          NGAP=0
0012          L=1
0013          GO TO 15
        C
0014       10 IF(LINE(L).NE.1H,.AND.LINE(L).NE.1H ) GO TO 20
0015          NGAP=NGAP+1
0016       15 L=L+1
0017          IF(L.GT.LMAX) GO TO 100
```

```
FORTRAN IV-PLUS V02-04G          17:37:47    22-MAR-78           PAGE 2
PARSE.FTN        /I4/TR:BLOCKS/WR

              GO TO 10
           20 IF(NGAP.EQ.0) GO TO 15
              DO 30 LL=L,LMAX
           30 LINE(LL-NGAP)=LINE(LL)
              LMAX=LMAX-NGAP
              L=L-NGAP
              NARG=NARG+1
              LPOINT(NARG)=L
              NGAP=0
              GO TO 15
          100 LPOINT(NARG+1)=LMAX-NGAP+1
        C
              IC=ICODE
              IARG=0
              DO 110 I=1,10
              ICN=IC/10
              LCODE(I)=IC-ICN*10
              IC=ICN
              IF(LCODE(I).EQ.0) GOTO 120
          110 IARG=IARG+1
          120 IF(IARG.GE.NARG) GO TO 130
          121 WRITE(6,700)
          700 FORMAT(30X,17HILLEGAL PARAMETER)
              IERR=4
              RETURN
          130 IF(NARG.EQ.0) RETURN
              DO 200 I=1,NARG
              L=LPOINT(I)
              NSIZE=LPOINT(I+1)-L
              DO 140 N=1,20
          140 MLINE(N)=1H
              IF(LCODE(I).EQ.3) GO TO 170
              L1=21-NSIZE
              DO 150 N=L1,20
              MLINE(N)=LINE(L)
          150 L=L+1
              ENCODE(20,151,WORD) MLINE
          151 FORMAT(20A1)
              GO TO (155,165), LCODE(I)
        C----------------INTEGER---------------------------------------
          155 DECODE(20,156,WORD,ERR=121) IVAR(I)
          156 FORMAT(I20)
              GO TO 200
        C----------------REAL------------------------------------------
          165 DECODE(20,166,WORD,ERR=121) RVAR(I)
          166 FORMAT(F20.0)
              GO TO 200
        C----------------ALPHANUMERIC----------------------------------
          170 NSIZE=MIN0(4,NSIZE)
              DO 180 N=1,NSIZE
              MLINE(N)=LINE(L)
          180 L=L+1
              ENCODE(4,181,AVAR(I)) (MLINE(J),J=1,4)
          181 FORMAT(4A1)
          200 CONTINUE
              RETURN
```

```
FORTRAN IV-PLUS V02-04G          17:38:13     22-MAR-78            PAGE 1
BOX.FTN          /14/TR:BLOCKS/WR

              SUBROUTINE BOX
        C
        C-------------------- ALL BLOCKS HAVE BEEN CREATED,
        C-------------------- BLOCKS CAN NOW BE BOXED -----
        C
              INCLUDE 'COMMON.FTN'
              COMMON A(5000)
              DIMENSION IA(1)
              EQUIVALENCE (A,IA)
              INCLUDE 'CBLOCK.FTN'
              LOGICAL LOCK
              LOGICAL RFLAG,UFLAG,EFLAG
              REAL LAME1,LAME2
              COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
             .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
             .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
             .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
             .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
             .                LOCK,LBLOCK
        C
              M4=M3+NBOXES
              M5=M4
        C-------------------- INITIALISE BOX POINTERS ---
              I1=M4-1
              DO 10 I=M3,I1
           10 IA(I)=0
        C-------------------- LOOP ON EACH BLOCK ---
              DO 50 NB=1,NBLOKS
              I2=IA(NB)
              NC=IA(I2+1)
              IC=I2+NVARB
        C-------------------- LOOP ON EACH CORNER ---
              DO 40 NP=1,NC
              X=A(IC)
              Y=A(IC+1)
              IBOX=MIN0(IFIX(X/BSIZE)+1,IBOXES)
              JBOX=MIN0(IFIX(Y/BSIZE),JBOXES-1)
              NBOX=JBOX*IBOXES+IBOX
              I3=M3+NBOX-1
              IA(M5+2)=IA(I3)
              IA(I3)=M5
              IA(M5)=NP
              IA(M5+1)=NB
              M5=M5+3
              IC=IC+3
           40 CONTINUE
        C
           50 CONTINUE
        C
              M6=M5+NBLOKM
              DO 60 I=M5,M6
           60 IA(I)=0
        C-------------------- CREATE EMPTY LIST TO END OF MEMORY ---
              NEMPT=M6
              I6=M6+4
```

```
FORTRAN IV-PLUS V02-04G          17:38:13     22-MAR-78              PAGE 2
BOX.FTN          /14/TR:BLOCKS/WR

0040          DO 80 I=I6,M7,13
0041          J=I
0042          IA(I)=I+9
0043       80 CONTINUE
0044          IA(J)=0
        C------------------- DETERMINE TIMESTEP ---
0045          TDEL=1.0E20
0046          DO 100 NB=1,NBLOKS
0047          I2=IA(NB)+7
0048          TN=2.0*SQRT(A(I2)/STIFN)
0049          TS=2.0*SQRT(A(I2)/STIFS)
0050          TDEL=AMIN1(TDEL,TN,TS)
0051      100 CONTINUE
0052          TDEL=TDEL*TFRAC
0053          WRITE(6,2000) TDEL
        C------------------- SET UP DAMPING TERMS ---
0054          BDT=BETA/TDEL
0055          CON1=1.0-ALPHA*TDEL/2.0
0056          CON2=1.0/(1.0+ALPHA*TDEL/2.0)
0057          CON1B=1.0-ALPHB*TDEL/2.0
0058          CON2B=1.0/(1.0+ALPHB*TDEL/2.0)
        C
0059          RETURN
        C
0060     2000 FORMAT(30X,17H TIME INCREMENT =,1PE12.4)
        C
0061          END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1   002120   552             RW,I,CON,LCL
$PDATA   000004     2             RW,D,CON,LCL
$IDATA   000060    24             RW,D,CON,LCL
$VARS    000104    34             RW,D,CON,LCL
$TEMPS   000006     3             RW,D,CON,LCL
.$$$$.   047040 10000             RW,D,OVR,GBL
CBLOCK   000460   152             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 052036 10767

BOX,0=BOX
```

```
FORTRAN IV-PLUS V02-04G          17:38:41     22-MAR-78              PAGE 1
CYCLE.FTN        /I4/TR:BLOCKS/WR

            SUBROUTINE CYCLE
      C
      C-------------------- DRIVER FOR ITERATIONS ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(5000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            LOGICAL LOCK
            LOGICAL RFLAG,UFLAG,EFLAG
            REAL LAME1,LAME2
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
           .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
           .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
           .                LOCK,LBLOCK
      C
            DO 100 NCYCLE=1,NCYC
            MCYCLE=MCYCLE+1
      C-------------------- UPDATE IF NECESSARY ---
            IF(UFLAG) CALL UPDAT
      C-------------------- SCAN ALL BLOCKS ---
            UDMAX=0.0
            DO 20 NBR=1,NBLOKS
            IBR=IA(NBR)
            CALL MOTION(A(IBR))
         20 CONTINUE
            DO 25 NB=1,NBLOKS
            IB=IA(NB)
         25 CALL STRESS(A(IB))
      C-------------------- EXIT IF NOTHING MOVED ---
            IF(UDMAX.EQ.0.0) GOTO 110
      C-------------------- UPDATE CONTACTS ? ---
            UMOST=UMOST+UDMAX*TDEL
            IF(UMOST.LT.1.0) GOTO 30
      C-------------------- YES ---
            UFLAG=.TRUE.
      C-------------------- SCAN ALL CONTACTS ---
         30 DO 50 NB=1,NBLOKS
            IBE=IA(NB)
            J6=M5+NB-1
         40 I6=IA(J6)
            IF(I6.EQ.0) GOTO 50
            JBC=IA(I6+3)
            IBC=IA(JBC)
            CALL FORD(A(I6),A(IBC),A(IBE))
            J6=I6+4
            GOTO 40
         50 CONTINUE
      C
      C-------------------- END CYCLE LOOP ---
      C
        100 CONTINUE
```

```
FORTRAN IV-PLUS V02-04G        17:38:41     22-MAR-78             PAGE 2
CYCLE.FTN        /I4/TR:BLOCKS/WR

        C
0038       110 CONTINUE
        C
0039           RETURN
        C
0040           END

PROGRAM SECTIONS

 NAME       SIZE                    ATTRIBUTES

$CODE1  001212    325               RW,I,CON,LCL
$IDATA  000022      9               RW,D,CON,LCL
$VARS   000040     16               RW,D,CON,LCL
$TEMPS  000010      4               RW,D,CON,LCL
.$$$$.  047040  10000               RW,D,OVR,GBL
CBLOCK  000460    152               RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 051024 10506

CYCLE,0=CYCLE
```

```
FORTRAN IV-PLUS V02-04G         17:39:02    22-MAR-78           PAGE 1
MOTION.FTN      /14/TR:BLOCKS/WR

            SUBROUTINE MOTION(B)
      C
      C------------------- LAW OF MOTION FOR A SINGLE BLOCK ---
      C
            INCLUDE 'CBLOCK.FTN'
            LOGICAL LOCK
            LOGICAL RFLAG,UFLAG,EFLAG
            REAL LAME1,LAME2
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
           .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
           .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
           .                LOCK,LBLOCK
            DIMENSION B(1)
            EQUIVALENCE (FIX,JFIX),(ANC,NC)
      C
            FIX=B(1)
      C------------------- IS THIS BLOCK FIXED ? ---
            IF(JFIX.NE.0) RETURN
      C------------------- NO ---
      C------------------- VELOCITIES FROM ACCELERATIONS ---
            B(5)=(B(5)*CON1+(B(10)/B(8)+GRAVX)*TDEL)*CON2
            B(6)=(B(6)*CON1+(B(11)/B(8)+GRAVY)*TDEL)*CON2
            B(7)=(B(7)*CON1+(B(12)/B(9))*TDEL)*CON2
            B(10)=0.0
            B(11)=0.0
            B(12)=0.0
      C
            ANC=B(2)
      C
      C------------------- DETERMINE AREA & WIDTH ---
            XMIN=XSIZE
            XMAX=0.0
            YMIN=YSIZE
            YMAX=0.0
            AREA=0.0
            K1=NVARB+1
            DO 50 NP=1,NC
            K2=K1+3
            IF(NP.EQ.NC) K2=NVARB+1
            X=B(K1)
            Y=B(K1+1)
            XMIN=AMIN1(XMIN,X)
            XMAX=AMAX1(XMAX,X)
            YMIN=AMIN1(YMIN,Y)
            YMAX=AMAX1(YMAX,Y)
            AREA=AREA+(B(K2)-X)*(B(K2+1)+Y)
         50 K1=K2
            AREA=AREA*2.0
            XW=XMAX-XMIN
            YW=YMAX-YMIN
            AM=TDEL/B(8)
      C------------------- EFFECTIVE MASSES ---
            EM11=AM/(XW*XW)
```

```
FORTRAN IV-PLUS V02-04G          17:39:02     22-MAR-78              PAGE 2
MOTION.FTN       /14/TR:BLOCKS/WR

              EM12=AM/(YW*YW)
              EM21=EM11
              EM22=EM12
        C-------------------- NEW STRAIN RATES ---
              B(13)=(B(13)*CON1B+(4.0*B(21)-B(17)*AREA)*EM11)*CON2B
              B(14)=(B(14)*CON1B+(4.0*B(22)-B(18)*AREA)*EM12)*CON2B
              B(15)=(B(15)*CON1B+(4.0*B(23)-B(19)*AREA)*EM21)*CON2B
              B(16)=(B(16)*CON1B+(4.0*B(24)-B(20)*AREA)*EM22)*CON2B
        C-------------------- UPDATE BLOCK CORNERS ---
              IC=NVARB+1
              DO 150 NPR=1,NC
              IC1=IC+1
              XARM=B(IC)-B(3)
              YARM=B(IC1)-B(4)
              XDC=B(5)+B(13)*XARM+(B(14)-B(7))*YARM
              YDC=B(6)+B(16)*YARM+(B(15)+B(7))*XARM
              UDMAX=AMAX1(UDMAX,ABS(XDC),ABS(YDC))
              IBX=B(IC)
              IBY=B(IC1)
              B(IC)=B(IC)+XDC*TDEL
              B(IC1)=B(IC1)+YDC*TDEL
              IF(IBX.NE.IFIX(B(IC)).OR.IBY.NE.IFIX(B(IC1))) CALL REBOX
          150 IC=IC+3
        C-------------------- RIGID BODY DISPLACEMENTS ---
              B(3)=B(3)+B(5)*TDEL
              B(4)=B(4)+B(6)*TDEL
        C-------------------------------------------------------------
              B(21)=0.0
              B(22)=0.0
              B(23)=0.0
              B(24)=0.0
              RETURN
        C
              END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

 $CODE1   002240   592            RW,I,CON,LCL
 $IDATA   000054    22            RW,D,CON,LCL
 $VARS    000154    54            RW,D,CON,LCL
 $TEMPS   000012     5            RW,D,CON,LCL
 CBLOCK   000460   152            RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 003162   825

MOTION,O=MOTION
```

```
FORTRAN IV-PLUS V02-04G          17:39:43     22-MAR-78            PAGE 1
FORD.FTN          /I4/TR:BLOCKS/WR

0001          SUBROUTINE FORD(C,BC,BE)
        C
        C------------------- FORCE DISPLACEMENT LAW FOR SINGLE CONTACT ---
        C
0002          INCLUDE 'CBLOCK.FTN'
0003 *        LOGICAL LOCK
0004 *        LOGICAL RFLAG,UFLAG,EFLAG
0005 *        REAL LAME1,LAME2
0006 *        COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *      .                 NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *      .                 TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *      .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *      .                 CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *      .                 G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *      .                 LOCK,LBLOCK
0007          DIMENSION C(1),BC(1),BE(1)
        C
        C------------------- RELATIVE X & Y VELOCITIES ACROSS CONTACT ---
0008          XCC=C(12)-BC(3)
0009          YCC=C(13)-BC(4)
0010          XCE=C(12)-BE(3)
0011          YCE=C(13)-BE(4)
0012          XD=BC(13)*XCC+(BC(14)-BC(7))*YCC+BC(5)
            .  -BE(13)*XCE-(BE(14)-BE(7))*YCE-BE(5)
0013          YD=BC(16)*YCC+(BC(15)+BC(7))*XCC+BC(6)
            .  -BE(16)*YCE-(BE(15)+BE(7))*XCE-BE(6)
        C------------------- SHEAR & NORMAL DISPLACEMENT INCREMENTS ---
0014          DUS=(XD*C(11)+YD*C(10))*TDEL
0015          DUN=(YD*C(11)-XD*C(10))*TDEL
        C------------------- NORMAL FORCE ---
0016          DFN=-DUN*STIFN
0017          C(8)=C(8)+DFN
0018          IF(LOCK) GOTO 10
        C------------------- TEST FOR TENSION ---
0019          IF(C(8).GE.0.0) GOTO 15
0020          C(8)=0.0
0021          C(9)=0.0
0022          DN=0.0
0023          DS=0.0
0024          GOTO 60
        C------------------- LOCKED JOINT ---
0025       10 FRICF=ABS(FRIC*C(8))
0026          GOTO 20
        C------------------- SHEAR FORCE ---
0027       15 FRICF=FRIC*C(8)
0028       20 DFS=DUS*STIFS
0029          C(9)=C(9)+DFS
0030          IF(ABS(C(9)).LE.FRICF) GOTO 40
0031          C(9)=SIGN(FRICF,C(9))
0032          DS=0.0
0033          GOTO 50
        C------------------- DASHPOT FORCES ---
0034       40 DS=BDT*DFS
0035       50 DN=BDT*DFN
        C------------------- GLOBAL CONTACT FORCES ---
0036       60 FYC=(C(9)+DS)*C(10)-(C(8)+DN)*C(11)
```

```
FORTRAN IV-PLUS V02-04G          17:39:43     22-MAR-78             PAGE 2
FORD.FTN          /14/TR:BLOCKS/WR

0037            FXC=(C(9)+DS)*C(11)+(C(8)+DN)*C(10)
          C------------------- ADD CONTRIBUTION TO BLOCK FORCES ---
0038            BC(10)=BC(10)-FXC
0039            BC(11)=BC(11)-FYC
0040            BC(12)=BC(12)-(FYC*XCC-FXC*YCC)
0041            BE(10)=BE(10)+FXC
0042            BE(11)=BE(11)+FYC
0043            BE(12)=BE(12)+(FYC*XCE-FXC*YCE)
          C------------------- APPLIED STRESS IN BLOCKS ---
0044            BC(21)=BC(21)-FXC*XCC
0045            BC(22)=BC(22)-FXC*YCC
0046            BC(23)=BC(23)-FYC*XCC
0047            BC(24)=BC(24)-FYC*YCC
0048            BE(21)=BE(21)+FXC*XCE
0049            BE(22)=BE(22)+FXC*YCE
0050            BE(23)=BE(23)+FYC*XCE
0051            BE(24)=BE(24)+FYC*YCE
          C
0052            RETURN
          C
0053            END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1   001444   402             RW,I,CON,LCL
$IDATA   000044    18             RW,D,CON,LCL
$VARS    000074    30             RW,D,CON,LCL
$TEMPS   000010     4             RW,D,CON,LCL
CBLOCK   000460   152             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 002274   606

FORD,O=FORD
```

```
FORTRAN IV-PLUS V02-04G        17:40:12    22-MAR-78           PAGE 1
STRESS.FTN       /14/TR:BLOCKS/WR

0001            SUBROUTINE STRESS(B)
          C
          C------------------ INTERNAL STRESSES FROM STRAINRATES ---
          C
0002            INCLUDE 'CBLOCK.FTN'
0003 *          LOGICAL LOCK
0004 *          LOGICAL RFLAG,UFLAG,EFLAG
0005 *          REAL LAME1,LAME2
0006 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *         .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC
     *         .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *         .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *         .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *         .                LOCK,LBLOCK
0007            DIMENSION B(1)
          C------------------ STRESS ROTATION CORRECTION TERMS ---
0008            S22C=(B(18)+B(19))*B(7)
0009            S12C=(B(17)-B(20))*B(7)
          C------------------ NEW STRESSES -----------------------
0010            B(17)=B(17)+(B(13)*LAME1+B(16)*LAME2-S22C)*TDEL
0011            B(18)=B(18)+(B(14)*2.0*G                +S12C)*TDEL
0012            B(19)=B(19)+(B(15)*2.0*G                +S12C)*TDEL
0013            B(20)=B(20)+(B(16)*LAME1+B(13)*LAME2+S22C)*TDEL
          C
0014            RETURN
0015            END

PROGRAM SECTIONS

 NAME       SIZE                   ATTRIBUTES

$CODE1  000274    94               RW,I,CON,LCL
$IDATA  000012     5               RW,D,CON,LCL
$VARS   000010     4               RW,D,CON,LCL
CBLOCK  000460   152               RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 000776   255

STRESS,O=STRESS
```

```
FORTRAN IV-PLUS V02-04G         17:40:21     22-MAR-78           PAGE 1
REBOX.FTN         /I4/TR:BLOCKS/WR

        SUBROUTINE REBOX
C
C------------------- ROUTINE TO REBOX A SINGLE BLOCK ---
C
        INCLUDE 'COMMON.FTN'
        COMMON A(5000)
        DIMENSION IA(1)
        EQUIVALENCE (A,IA)
        INCLUDE 'CBLOCK.FTN'
        LOGICAL LOCK
        LOGICAL RFLAG,UFLAG,EFLAG
        REAL LAME1,LAME2
        COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     .                  NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     .                  TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     .                  YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     .                  CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     .                  G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     .                  LOCK,LBLOCK
C
        NB=NBR
        IB=IBR
        NP=NPR
        IC=IB+NVARB+3*(NP-1)
C------------------- ARE WE AT EDGE OF DOMAIN ? ---
        XE=A(IC)
        YE=A(IC+1)
        IF(XE.GT.0.0.AND.XE.LT.XSIZE.AND.
     .     YE.GT.0.0.AND.YE.LT.YSIZE) GOTO 20
C------------------- YES, SET MASTER FIX FLAG ---
        IA(IB)=2
        A(IB+4)=0.0
        A(IB+5)=0.0
        A(IB+6)=0.0
        A(IB+12)=0.0
        A(IB+13)=0.0
        A(IB+14)=0.0
        A(IB+15)=0.0
        RETURN
C------------------- NO, WHICH BOX SHOULD CORNER BE IN ? ---
     20 NBOX=IFIX(XE/BSIZE) + IFIX(YE/BSIZE)*IBOXES + 1
C------------------- SEARCH THIS BOX ---
        J4N=M3+NBOX-1
     30 I4N=IA(J4N)
        IF(I4N.EQ.0) GOTO 40
        IF(NB.EQ.IA(I4N+1).AND.NP.EQ.IA(I4N)) RETURN
        J4N=I4N+2
        GOTO 30
C------------------- SEARCH THE SURROUNDING BOXES ---
     40 NXL=MAX0(MOD(NBOX-1,IBOXES),1)
        NXU=MIN0(NXL+2,IBOXES)
        NYL=MAX0(NBOX/IBOXES,1)
        NYU=MIN0(NYL+2,JBOXES)
        DO 80 JBOX=NYL,NYU
        MBOX=(JBOX-1)*IBOXES+NXL-1
        DO 70 IBOX=NXL,NXU
```

```
FORTRAN IV-PLUS V02-04G         17:40:21     22-MAR-78             PAGE 2
REBOX.FTN        /14/TR:BLOCKS/WR

0041          MBOX=MBOX+1
0042          IF(MBOX.EQ.NBOX) GOTO 70
0043          J4M=M3+MBOX-1
0044       50 I4M=IA(J4M)
0045          IF(I4M.EQ.0) GOTO 70
0046          IF(NB.EQ.IA(I4M+1).AND.NP.EQ.IA(I4M)) GOTO 60
0047          J4M=I4M+2
0048          GOTO 50
        C------------------- SWAP ENTRIES FOR THIS CORNER ---
0049       60 IA(J4M)=IA(I4M+2)
0050          IA(J4N)=I4M
0051          IA(I4M+2)=0
0052          RETURN
        C------------------- END OF SURROUNDING BOXES SCAN ---
0053       70 CONTINUE
0054       80 CONTINUE
0055          WRITE(6,3000) NP,NB
0056          EFLAG=.TRUE.
0057          CALL FINISH
0058          RETURN
        C
0059     3000 FORMAT(24H ERROR IN REBOX : CORNER,I3,
             .         9H OF BLOCK,I4,20H NOT IN ADJACENT BOX)
        C
0060          END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1  002010   516              RW,I,CON,LCL
$PDATA  000010     4              RW,D,CON,LCL
$IDATA  000140    48              RW,D,CON,LCL
$VARS   000110    36              RW,D,CON,LCL
$TEMPS  000010     4              RW,D,CON,LCL
.$$$$.  047040 10000              RW,D,OVR,GBL
CBLOCK  000460   152              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 052020 10760

REBOX,0=REBOX
```

```
FORTRAN IV-PLUS V02-04G          17:40:53     22-MAR-78              PAGE 1
UPDAT.FTN        /14/TR:BLOCKS/WR

0001             SUBROUTINE UPDAT
           C
           C-------------------- UPDATE ALL CONTACTS ---
           C
0002             INCLUDE 'COMMON.FTN'
0003 *           COMMON A(5000)
0004 *           DIMENSION IA(1)
0005 *           EQUIVALENCE (A,IA)
0006             INCLUDE 'CBLOCK.FTN'
0007 *           LOGICAL LOCK
0008 *           LOGICAL RFLAG,UFLAG,EFLAG
0009 *           REAL LAME1,LAME2
0010 *           COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *          .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *          .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *          .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *          .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *          .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *          .                LOCK,LBLOCK
0011             LOGICAL FIRST
           D     LOGICAL DEBUG
           D     DATA DEBUG/.TRUE./
0012             DATA TOL /1.0/
           C
           C-------------------- SCAN EACH BLOCK ---
0013             DO 500 NB=1,NBLOKS
0014             I2=IA(NB)
0015             NC=IA(I2+1)
           C-------------------- SCAN EACH EDGE OF BLOCK ---
0016             IEND2=I2+NVARB
0017             DO 400 NP=1,NC
0018             FIRST=.TRUE.
0019             IEND1=IEND2
0020             IEND2=IEND1+3
0021             IF(NP.EQ.NC) IEND2=I2+NVARB
           C-------------------- DETERMINE BOXES TO BE SEARCHED ---
0022             X1=A(IEND1)
0023             X2=A(IEND2)
0024             Y1=A(IEND1+1)
0025             Y2=A(IEND2+1)
0026             XDIF=X2-X1
0027             YDIF=Y2-Y1
0028             Z=SQRT(XDIF*XDIF+YDIF*YDIF)
0029             A(IEND1+2)=Z
0030             XX1=AMIN1(X1,X2)
0031             XX2=AMAX1(X1,X2)
0032             YY1=AMIN1(Y1,Y2)
0033             YY2=AMAX1(Y1,Y2)
0034             NXL=IFIX((XX1-TOL)/BSIZE)+1
0035             NXU=MIN0(IFIX((XX2+TOL)/BSIZE)+1,IBOXES)
0036             NYL=IFIX((YY1-TOL)/BSIZE)+1
0037             NYU=MIN0(IFIX((YY2+TOL)/BSIZE)+1,JBOXES)
           D     IF(DEBUG) PRINT*,' NPE,NXYLU',NP,NXL,NXU,NYL,NYU
           C-------------------- SEARCH EACH CANDIDATE BOX ---
0038             DO 350 JBOX=NYL,NYU
0039             NBOX=(JBOX-1)*IBOXES+NXL-1
```

```
FORTRAN IV-PLUS V02-04G          17:40:53    22-MAR-78            PAGE 2
UPDAT.FTN        /I4/TR:BLOCKS/WR

0040          DO 300 IBOX=NXL,NXU
0041          NBOX=NBOX+1
0042          I4=IA(M3+NBOX-1)
        C-------------------- END OF BOX LIST ? ---
0043      210 CONTINUE
        D     IF(DEBUG) PRINT*,' NBOX,I4,NPC,NBC',NBOX,I4,IA(I4),IA(I4+1)
0044          IF(I4.EQ.0) GOTO 300
        C-------------------- NO, IS THIS BLOCK NB ? ---
0045          IF(IA(I4+1).NE.NB) GOTO 220
        C-------------------- YES ---
        C-------------------- GET NEXT ENTRY IN THIS BOX ---
0046      215 I4=IA(I4+2)
0047          GOTO 210
        C-------------------- FIRST TIME THROUGH ? ---
0048      220 IF(.NOT.FIRST) GOTO 230
        C-------------------- YES, COMPUTE COS, SIN  FOR THIS EDGE ---
0049          FIRST=.FALSE.
0050          COSA=XDIF/Z
0051          SINA=YDIF/Z
        C-------------------- COMPUTE CORNER COORDINATES RELATIVE TO EDGE ---
0052      230 I2C=IA(I4+1)
0053          I2C=IA(I2C)
0054          IC=I2C+IA(I4)*3+NVARB-3
0055          YT=(A(IC+1)-Y1)*COSA
             .  -(A(IC)  -X1)*SINA
        D     IF(DEBUG) PRINT*,' YT',YT
0056          IF(YT.GT.1.0) GOTO 215
0057          IF(YT.LE.-3.0) GOTO 215
0058          XT=(A(IC)  -X1)*COSA
             .  +(A(IC+1)-Y1)*SINA
        D     IF(DEBUG) PRINT*,' XT',XT
0059          IF(XT.GT.Z) GOTO 215
0060          IF(XT.LT.0.0) GOTO 215
        C-------------------- CONTACT LIST FOR BLOCK NB ---
0061          J6=M5+NB-1
0062          I6=IA(J6)
        C-------------------- END OF LIST ? ---
0063      235 CONTINUE
0064          IF(I6.EQ.0) GOTO 250
        C-------------------- NO. SAME CORNER AND EDGE ? ---
0065          IF(IA(I4).EQ.IA(I6+2).AND.IA(I4+1).EQ.IA(I6+3)
             .    .AND.NP.EQ.IA(I6+1)) GOTO 240
        C-------------------- NO. GET NEXT ENTRY IN CONTACT LIST ---
        D      IF(DEBUG) PRINT*,' GET NEXT ENTRY'
0066          J6=I6+4
0067          I6=IA(J6)
0068          GOTO 235
        C-------------------- CONTACT ALREADY STORED ---
0069      240 IF(YT.GT.-2.0) GOTO 245
        C-------------------- APPLY DRIFT CORRECTION ---
0070          WRITE(6,3000)
        C-------------------- UPDATE CONTACT DATA ---
0071      245 A(I6+9)=SINA
0072          A(I6+10)=COSA
0073          A(I6+11)=A(IC)
0074          A(I6+12)=A(IC+1)
```

```
FORTRAN IV-PLUS V02-04G          17:40:53    22-MAR-78            PAGE 3
UPDAT.FTN        /I4/TR:BLOCKS/WR

0075              IA(I6)=1
            D     IF(DEBUG) PRINT*,' UPDATE CONTACT DATA'
0076              GOTO 215
            C------------------- NEW CONTACT ? ---
0077          250 CONTINUE
            D     IF(DEBUG) PRINT*,' GOT TO 250!'
0078              IF(YT.GT.0.0) GOTO 215
            C------------------- YES ---
            D     IF(DEBUG) PRINT*,' NEW CONTACT'
0079              I6=NEMPT
0080              ICR=IC-3
0081              IF(IA(I4).EQ.1) ICR=IC+3*(IA(I2C+1)-1)
0082              YTR=(A(ICR+1)-Y1)*COSA
                .    -(A(ICR)   -X1)*SINA
            D     IF(DEBUG) PRINT*,' YTR',YTR
0083              IF(YTR.LE.-2.0) GOTO 215
0084              ICL=IC+3
0085              IF(IA(I4).EQ.IA(I2C+1)) ICL=I2C+NVARB
0086              YTL=(A(ICL+1)-Y1)*COSA
                .    -(A(ICL)   -X1)*SINA
            D     IF(DEBUG) PRINT*,' YTL',YTL
0087              IF(YTL.LE.-2.0) GOTO 215
            C------------------- ANY SPACE AVAILABLE IN EMPTY LIST ? ---
0088              IF(IA(NEMPT+4).NE.0) GOTO 260
0089              WRITE(6,3001)
0090              CALL FINISH
            C------------------- NEW CONTACT ---
0091          260 A(I6+5)=0.0
0092              A(I6+6)=0.0
0093              A(I6+7)=0.0
0094              A(I6+8)=0.0
0095              IA(I6+1)=NP
0096              IA(I6+2)=IA(I4)
0097              IA(I6+3)=IA(I4+1)
0098              NEMPT=IA(I6+4)
0099              IA(J6)=I6
0100              IA(I6+4)=0
            D     IF(DEBUG) PRINT*,' REALLY IS A NEW CONTACT!!!'
0101              GOTO 245
            C------------------- END OF BOX SCAN ---
0102          300 CONTINUE
0103          350 CONTINUE
            C------------------- END OF EDGE SCAN ---
0104          400 CONTINUE
            C------------------- SCAN CONTACT LIST FOR PRESERVE FLAGS ---
0105              J6=M5+NB-1
0106              I6=IA(J6)
            C------------------- END OF LIST ? ---
0107          410 IF(I6.EQ.0) GOTO 490
            C------------------- NO ---
            C------------------- IS THE PRESERVE FLAG SET ? ---
0108              IF(IA(I6).EQ.0) GOTO 420
            C------------------- YES ---
            D     IF(DEBUG) PRINT*,' PRESERVE FLAG SET'
0109              IA(I6)=0
0110          415 J6=I6+4
```

```
FORTRAN IV-PLUS V02-04G         17:40:53    22-MAR-78            PAGE 4
UPDAT.FTN        /I4/TR:BLOCKS/WR

0111          GOTO 430
        C------------------- NO ---
0112      420 IF(LOCK) GOTO 415
0113          IA(J6)=IA(I6+4)
0114          IA(I6+4)=NEMPT
0115          NEMPT=I6
        D     IF(DEBUG) PRINT*,' PRESERVE FLAG NOT SET'
        C------------------- GET NEXT CONTACT ---
0116      430 I6=IA(J6)
0117          GOTO 410
        C------------------- END OF BLOCK SCAN ---
0118      490 CONTINUE
        D     IF(DEBUG) DEBUG=.FALSE.
0119      500 CONTINUE
        C
0120          NUPDAT=NUPDAT+1
0121          UFLAG=.FALSE.
0122          UMOST=0.0
0123          RETURN
        C
0124     3000 FORMAT(30X,26H DRIFT CORRECTION REQUIRED)
0125     3001 FORMAT(30X,32H NO MORE MEMORY FOR CONTACT LIST)
        C
0126          END

PROGRAM SECTIONS

 NAME       SIZE                   ATTRIBUTES

$CODE1   004236  1103              RW,I,CON,LCL
$PDATA   000004     2              RW,D,CON,LCL
$IDATA   000140    48              RW,D,CON,LCL
$VARS    000234    78              RW,D,CON,LCL
$TEMPS   000022     9              RW,D,CON,LCL
.$$$$.   047040 10000              RW,D,OVR,GBL
CBLOCK   000460   152              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 054400 11392

UPDAT,0=UPDAT
```

```
FORTRAN IV-PLUS V02-04G          17:41:56     22-MAR-78            PAGE 1
DUMP.FTN          /14/TR:BLOCKS/WR

              SUBROUTINE DUMP
       C
       C------------------- ROUTINE TO PRINT MEMORY ALLOCATION AND CONTENTS ---
       C
              INCLUDE 'COMMON.FTN'
              COMMON A(5000)
              DIMENSION IA(1)
              EQUIVALENCE (A,IA)
              INCLUDE 'CBLOCK.FTN'
              LOGICAL LOCK
              LOGICAL RFLAG,UFLAG,EFLAG
              REAL LAME1,LAME2
              COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
             .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
             .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB
             .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
             .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
             .                LOCK,LBLOCK
       C
              IF(LOC2.EQ.0) RETURN
              WRITE(6,2000)
              WRITE(6,2005) M1,M2,M3,M4,M5,M6,M7,NBLOKS,NCYC,NEMPT,MCYCLE
              IF(LOC2.LT.0) GOTO 100
       C------------------- DUMP CONSECUTIVE MEMORY LOCATIONS ---
              WRITE(6,2009)
              I2=((LOC1-1)/10)*10
           10 I1=I2+1
              I2=I1+9
              WRITE(6,2001) (IA(I),I=I1,I2),I2
              IF(I2.LT.LOC2) GOTO 10
              GOTO 500
       C
       C------------------- DUMP BY BOX ---
          100 WRITE(6,2002)
              DO 120 NBOX=1,NBOXES
              I3=IA(M3+NBOX-1)
       C------------------- ANY MORE ENTRIES ? ---
          110 IF(I3.EQ.0) GOTO 120
       C------------------- NO, PRINT BLOCK,CORNER ---
              WRITE(6,2008) NBOX,IA(I3+1),IA(I3)
              I3=IA(I3+2)
              GOTO 110
          120 CONTINUE
       C------------------- CONTENTS OF EACH BLOCK ---
              WRITE(6,2006)
              DO 130 NB=1,NBLOKS
              IF=IA(NB)
              IL=IF+NVARB-1+3*IA(IF+1)
              WRITE(6,2003) NB,IA(IF),IA(IF+1),(A(I),I=IF+2,IL)
          130 CONTINUE
       C------------------- DUMP CONTACT DATA ---
              IF(M5.EQ.0) GOTO 500
              WRITE(6,2007)
              DO 150 NB=1,NBLOKS
              J6=M5+NB-1
```

```
FORTRAN IV-PLUS V02-04G          17:41:56     22-MAR-78            PAGE 2
DUMP.FTN          /I4/TR:BLOCKS/WR

        140 I6=IA(J6)
            IF(I6.EQ.0) GOTO 150
            WRITE(6,2004) NB,(IA(I),I=I6,I6+4),
                            (A(I),I=I6+5,I6+12)
            J6=I6+4
            GOTO 140
        150 CONTINUE
      C-------------------
        500 WRITE(6,2000)
      C
            RETURN
      C
       2000 FORMAT(1X,130(1H-))
       2001 FORMAT(1X,10012,I6)
       2002 FORMAT(10X,3HBOX,7X,5HBLOCK,6X,6HCORNER)
       2003 FORMAT(/1X,3I3,1P11E10.2/(10X,1P11E10.2))
       2004 FORMAT(/1X,6I10/1X,1P8E10.2)
       2005 FORMAT(9X,2HM1,8X,2HM2,8X,2HM3,8X,2HM4,8X,2HM5,8X,2HM6,
          .         8X,2HM7,4X,6HNBLOKS,6X,4HNCYC,5X,5HNEMPT,4X,6HMCYCLE/
          .         1X,11I10)
       2006 FORMAT(11H BLOCK DATA,10(1H-)/1X,9H NB IF NC,8X,2HXC,8X,2HYC,
          .         6X,4HXDOT,6X,4HYDOT,6X,4HTDOT,6X,4HMASS,
          .         7X,3HMOI,5X,5HXFSUM,5X,5HYFSUM,6X,4HMSUM,6X,4HED11
          .        /16X,4HED12,6X,4HED21,6X,4HED22,6X,4HSI11,6X,4HSI12,
          .         6X,4HSI21,6X,4HSI22,6X,4HSA11,6X,4HSA12,6X,4HSA21,
          .         6X,4HSA22)
       2007 FORMAT(13H CONTACT DATA,10(1H-)/8X,3HNBE,7X,3HPRE,7X,3HNPE,7X,
          .         3HNPC,7X,3HNBC,6X,4HLINK/10X,1HS,9X,1HN,8X,2HFN,8X,2HFS,
          .         7X,3HSIN,7X,3HCOS,7X,3HXCP,7X,3HYCP)
       2008 FORMAT(1X,3I12)
       2009 FORMAT(1X,30(1H*),19HVALUES ARE IN OCTAL,30(1H*))
      C
            END

PROGRAM SECTIONS

 NAME        SIZE                      ATTRIBUTES

$CODE1   002272    605                 RW,I,CON,LCL
$PDATA   000010      4                 RW,D,CON,LCL
$IDATA   001026    267                 RW,D,CON,LCL
$VARS    000050     20                 RW,D,CON,LCL
$TEMPS   000016      7                 RW,D,CON,LCL
.$$$$.   047040  10000                 RW,D,OVR,GBL
CBLOCK   000460    152                 RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 053136 11055

NO FPP INSTRUCTIONS GENERATED

DUMP,0=DUMP
```

```
FORTRAN IV-PLUS V02-04G          17:42:37     22-MAR-78            PAGE 1
BPLOT.FTN         /I4/TR:BLOCKS/WR

            SUBROUTINE BPLOT
      C
      C------------------- PLOT A SNAPSHOT OF THE GEOMETRY ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(5000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            LOGICAL LOCK
            LOGICAL RFLAG,UFLAG,EFLAG
            REAL LAME1,LAME2
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
           .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
           .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
           .                LOCK,LBLOCK
      C
            SCREEN=10.0
            FACT=SCREEN/AMAX1(XSIZE,YSIZE)
      C------------------- PLOT EACH BLOCK ---
            DO 100 NB=1,NBLOKS
            I2=IA(NB)
            NC=IA(I2+1)
            XC=FACT*A(I2+2)
            YC=FACT*A(I2+3)
      C------------------- FIXED ? ---
            IF(IA(I2).EQ.0) GOTO 20
      C------------------- YES, ALREADY PLOTTED ? ---
            IF(IA(I2).GT.2) GOTO 100
      C------------------- NO ---
            IA(I2)=IA(I2)+2
            CALL SYMBOL(XC,YC,0.2,1HF,0.0,1)
         20 IC=I2+NVARB
            X=FACT*A(IC)
            Y=FACT*A(IC+1)
            CALL PLOT(X,Y,3)
            DO 50 NP=2,NC
            IC=IC+3
            X=FACT*A(IC)
            Y=FACT*A(IC+1)
            CALL PLOT(X,Y,2)
         50 CONTINUE
            X=FACT*A(I2+NVARB)
            Y=FACT*A(I2+NVARB+1)
            CALL PLOT(X,Y,2)
      C------------------- END OF BLOCK LOOP ---
        100 CONTINUE
      C
            CALL PLOT(0.0,0.0,3)
      C
            RETURN
      C
            END
```

```
FORTRAN IV-PLUS V02-04G          17:43:00     22-MAR-78            PAGE 1
FINISH.FTN       /I4/TR:BLOCKS/WR

0001              SUBROUTINE FINISH
            C
            C------------------- TIDY UP AND STOP ---
            C
0002              INCLUDE 'COMMON.FTN'
0003 *            COMMON A(5000)
0004 *            DIMENSION IA(1)
0005 *            EQUIVALENCE (A,IA)
0006              INCLUDE 'CBLOCK.FTN'
0007 *            LOGICAL LOCK
0008 *            LOGICAL RFLAG,UFLAG,EFLAG
0009 *            REAL LAME1,LAME2
0010 *            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *           .                NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *           .                CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *           .                G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *           .                LOCK,LBLOCK
            C
0011              CALL PLOTND
0012              WRITE(6,2000) MCYCLE,NUPDAT
            C
            C------------------- WRITE RESTART FILE IF NO ERRORS ---
0013              IF(EFLAG) GOTO 100
0014              REWIND 1
0015              WRITE(1) (HED(I),I=1,LBLOCK)
0016              WRITE(1) (A(I),I=1,M7)
0017              WRITE(6,2001)
0018          100 STOP
            C
0019         2000 FORMAT(30X,13H TOTAL CYCLES,I10/
                 .          30X,13H NO. UPDATES ,I10)
0020         2001 FORMAT(30X,32H A RESTART FILE HAS BEEN WRITTEN)
            C
0021              END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1  000364    122              RW,I,CON,LCL
$IDATA  000120     40              RW,D,CON,LCL
$VARS   000004      2              RW,D,CON,LCL
.$$$$.  047040 10000               RW,D,OVR,GBL
CBLOCK  000460    152              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 050230 10316

NO FPP INSTRUCTIONS GENERATED

FINISH,0=FINISH
```

```
FORTRAN IV-PLUS V02-04G          17:43:17     22-MAR-78            PAGE 1
CHECK.FTN         /14/TR:BLOCKS/WR

0001            SUBROUTINE CHECK
        C
        C-------------------- MOMENTUM AND ENERGY CHECK ---
        C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(5000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          LOGICAL LOCK
0008 *          LOGICAL RFLAG,UFLAG,EFLAG
0009 *          REAL LAME1,LAME2
0010 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,M5,M6,M7,
     *     .                    NBLOKS,NCYC,MCYCLE,NEMPT,RFLAG,UFLAG,EFLAG,TFRAC,
     *     .                    TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *     .                    YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,ALPHB,
     *     .                    CON1,CON2,ALPHA,NVARB,NBR,IBR,NPR,LAME1,LAME2,
     *     .                    G,CON1B,CON2B,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,YIELD,
     *     .                    LOCK,LBLOCK
        C
0011            WRITE(6,3000)
0012            GO TO 200
0013            XMOM=0.0

[XMOM=0.0]
ERROR  26
W NO PATH TO THIS STATEMENT

0014            YMOM=0.0
0015            TMOM=0.0
0016            TARM=0.0
0017            XKE=0.0
0018            YKE=0.0
0019            TKE=0.0
0020            DO 100 NB=1,NBLOKS
0021            I2=IA(NB)
0022            XMOM=XMOM+A(I2+11)*A(I2+5)
0023            YMOM=YMOM+A(I2+11)*A(I2+6)
0024            TMOM=TMOM+A(I2+12)*A(I2+7)
0025            TARM=TARM+A(I2+11)*(A(I2+2)*A(I2+6)-A(I2+3)*A(I2+5))
0026            XKE=XKE+0.5*A(I2+11)*A(I2+5)**2
0027            YKE=YKE+0.5*A(I2+11)*A(I2+6)**2
0028            TKE=TKE+0.5*A(I2+12)*A(I2+7)**2
0029            WRITE(6,2001) XMOM,YMOM,TMOM,TARM,XKE,YKE,TKE
0030        100 CONTINUE
        C
0031            ESUM=XKE+YKE+TKE
0032            TSUM=TMOM+TARM
        C
0033            WRITE(6,2000) XMOM,YMOM,TMOM,TARM,TSUM,XKE,YKE,TKE,ESUM
        C
0034        200 RETURN
        C
0035       2000 FORMAT(9H MOMENTUM,11X,1HX,11X,1HY,2X,10HROTATIONAL/
           .           9X,1P5E12.4//
           .           9H ENERGY  ,11X,1HX,11X,1HY,2X,10HROTATIONAL,7X,5HTOTAL/
```

```
FORTRAN IV-PLUS V02-04G          17:43:17    22-MAR-78            PAGE 2
CHECK.FTN        /I4/TR:BLOCKS/WR

              .        9X,1P4E12.4)
0036       2001 FORMAT(1X,1P7E12.4)
0037       3000 FORMAT(30X,17HNOT AVAILABLE YET)
          C
0038            END

PROGRAM SECTIONS

 NAME        SIZE                    ATTRIBUTES

$CODE1   000674    222              RW,I,CON,LCL
$IDATA   000176     63              RW,D,CON,LCL
$VARS    000054     22              RW,D,CON,LCL
.$$$$.   047040  10000              RW,D,OVR,GBL
CBLOCK   000460    152              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 050666 10459

CHECK,0=CHECK
```

APPENDIX XIV: LISTING OF PROGRAM RBMC

```
FORTRAN IV-PLUS V02-04G          14:34:43    29-MAR-78            PAGE 1
RBMC.FTN        /14/TR:BLOCKS/WR

0001            PROGRAM RBMC
          C
          C------------------ RIGID BLOCK MODEL ---
          C
          C------------------ ORIGINAL PROGRAM BY P.A.CUNDALL
          C------------------ TRANSLATION INTO FORTRAN BY P.J.BERESFORD
          C------------------ INTRODUCTION OF CRACKING BY N.C.LAST,MARCH 1978
          C
          C
          C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(3000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *         .                  NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *         .                  TOEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                  YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *         .                  CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *         .                  NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *          LOGICAL EFLAG
          C
0009            DATA STIFN,STIFS,FRIC,BETA/2*1.0E8,0.0,0.0/
0010            DATA GRAVY,GRAVX/-9.81,0.0/
0011            DATA M4,MCYCLE,NUPDAT,LBLOCK/3000,0,0,68/
0012            DATA EFLAG/.FALSE./
0013            DATA NVARB,NFRAG/14,10/
          C
0014            CALL PLOTST(.025,'CM')
0015            CALL SETUPC
0016         10 CALL NEXTC
0017            CALL CYCLEC
0018            GO TO 10
          C
0019            END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1   000076    31             RW,I,CON,LCL
$PDATA   000010     4             RW,D,CON,LCL
$IDATA   000010     4             RW,D,CON,LCL
.$$$$.   027340  6000             RW,D,OVR,GBL
CBLOCK   000424   138             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 030102  6177

NO FPP INSTRUCTIONS GENERATED
```

```
            SUBROUTINE SETUPC
      C
            INCLUDE 'COMMON.FTN'
   *        COMMON A(3000)
   *        DIMENSION IA(1)
   *        EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
   *        COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
   *       .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
   *       .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
   *       .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
   *       .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
   *       .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
   *        LOGICAL EFLAG
      C
            DIMENSION CARD(20),WORD(10)
            BYTE DAY(10),TIM(10)
      C
            DATA WORD /4HSTAR,4HREST,4HBLOC,4HBOXE,4HXLIM,
           .           4HYLIM,4H****,4HFRAC,4HDENS,4HTSTR/
      C
            JOB=0
            CALL DATE(DAY)
            CALL TIME(TIM)
            WRITE(6,2000) DAY,TIM
      C------------------- READ NEXT CARD ---
         10 READ(5,1000) CARD
            CALL TIME(TIM)
            WRITE(6,2001) CARD,TIM
      C
            DO 20 I=1,10
            IF(CARD(1).EQ.WORD(I)) GOTO 30
         20 CONTINUE
      C
            WRITE(6,3000)
            GOTO 10
      C
         30 IF(I.GT.2.AND.JOB.EQ.0) GOTO 60
            GOTO (110,120,130,140,150,
           .      160,900,170, 180, 190), I
      C
         50 WRITE(6,3001)
            GOTO 10
      C
         60 WRITE(6,3002)
            GOTO 10
      C------------------- START OF NEW RUN ---
        110 JOB=1
            DO 111 I=1,20
        111 HED(I)=CARD(I)
            GOTO 10
      C------------------- RESTART RUN ---
        120 JOB=2
            READ(1) (HED(I),I=1,LBLOCK)
            READ(1) (A(I),I=1,M4)
            WRITE(6,2003) MCYCLE
```

```
            RETURN
      C------------------- MAXIMUM NUMBER OF BLOCKS ---
        130 DECODE(20,1001,CARD) NBLOKM
            GOTO 10
      C------------------- NUMBER OF BOXES ---
        140 DECODE(40,1001,CARD) IBOXES,JBOXES,IBSIZE
            BSIZE=FLOAT(IBSIZE)
            NBOXES=IBOXES*JBOXES
            GOTO 10
      C------------------- PROBLEM X-LIMITS ---
        150 DECODE(30,1002,CARD) XL,XU
            IF(XL.LT.XU) GOTO 10
            TEMP=XL
            XL=XU
            XU=TEMP
            GOTO 10
      C------------------- PROBLEM Y-LIMITS ---
        160 DECODE(30,1002,CARD) YL,YU
            IF(YL.LT.YU) GOTO 10
            TEMP=YL
            YL=YU
            YU=TEMP
            GOTO 10
      C------------------- FRACTION OF CRITICAL TIMESTEP ---
        170 DECODE(20,1002,CARD) TFRAC
            GOTO 10
      C------------------- DENSITY OF BLOCKS ---
        180 DECODE(20,1003,CARD) RHO
            GO TO 10
      C------------------- MAXIMUM TENSILE STRENGTH ---
        190 DECODE(20,1003,CARD) TMAX
            GO TO 10
      C------------------- SETUP FINISHED ---
        900 CONTINUE
      C------------------- INITIALISE SOME VARIABLES ---
            UMOST=0.0
            NBLOKS=0
            XSIZE=FLOAT(IBOXES)*BSIZE
            YSIZE=FLOAT(JBOXES)*BSIZE
            XF=XSIZE/(XU-XL)
            YF=YSIZE/(YU-YL)
            SFACT=AMIN1(XF,YF)
            M1=1
            M2=M1+(NFRAG+1)*NBLOKM
            M3=M2+NBOXES
            NEMPTG=M3
            NEMPTC=0
            NEMPTD=0
            I1=M2+NBOXES-1
            DO 5 I=M2,I1
          5 IA(I)=0
            WRITE(6,2002) NBLOKM,RHO,TMAX,NBOXES,XL,XU,YL,YU,BSIZE,SFACT
            RETURN
      C
       1000 FORMAT(20A4)
       1001 FORMAT(10X,3I10)
```

```
FORTRAN IV-PLUS V02-04G          14:34:48    29-MAR-78           PAGE 4
RBMC.FTN          /I4/TR:BLOCKS/WR

0084      1002 FORMAT(10X,5F10.0)
0085      1003 FORMAT(10X,F10.0)
0086      2000 FORMAT(30X,26H RBMC - RIGID BLOCK MODEL.,55X,10A1,1X,10A1/
               .        30X,26H -------------------------- / )
0087      2001 FORMAT(1X,4H+++ ,20A4,4H +++,32X,10A1)
0088      2002 FORMAT(/30X,25H MAXIMUM NUMBER OF BLOCKS,I5/
               .         30X,25H DENSITY OF BLOCKS        ,F10.2/
               .         30X,25H TENSILE STRENGTH         ,F10.2/
               .         30X,25H NUMBER OF BOXES          ,I5/
               .         30X,25H X-LIMITS                 ,2F10.2/
               .         30X,25H Y LIMITS                 ,2F10.2/
               .         30X,25H BSIZE                    ,F10.2/
               .         30X,25H SFACT                    ,F10.2)
0089      2003 FORMAT(30X,31H RESTART RUN. CURRENT CYCLES ..,I10)
0090      3000 FORMAT(28H !!! ERROR : ILLEGAL COMMAND)
0091      3001 FORMAT(34H !!! ERROR : COMMAND NOT AVAILABLE)
0092      3002 FORMAT(48H !!! ERROR : 'START' OR 'RESTART' CARD NOT FOUND)
          C
0093           END

PROGRAM SECTIONS

 NAME       SIZE                 ATTRIBUTES

$CODE1  002534   686             RW,I,CON,LCL
$PDATA  000026    11             RW,D,CON,LCL
$IDATA  001106   291             RW,D,CON,LCL
$VARS   000250    84             RW,D,CON,LCL
$TEMPS  000004     2             RW,D,CON,LCL
.$$$$.  027340  6000             RW,D,OVR,GBL
CBLOCK  000424   138             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 034130  7212
```

```
FORTRAN IV-PLUS V02-04G          14:35:09     29-MAR-78            PAGE 5
RBMC.FTN          /I4/TR:BLOCKS/WR

0001              SUBROUTINE NEXTC
            C
0002              INCLUDE 'COMMON.FTN'
0003 *            COMMON A(3000)
0004 *            DIMENSION IA(1)
0005 *            EQUIVALENCE (A,IA)
0006              INCLUDE 'CBLOCK.FTN'
0007 *            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *          .                 NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *          .                 TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *          .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *          .                 CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *          .                 NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *            LOGICAL EFLAG
            C
0009              DIMENSION CARD(20),WORD(20),X(50),Y(50)
0010              BYTE TIM(10)
            C
0011              DATA WORD /4HCREA,4HDELE,4HDUMP,4HCYCL,4HSTOP,
                .            4HPLOT,4H****,4HRSET,4HISET,4HZZZZ,
                .            4HGRAV,4HSTIF,4HDAMP,4HFRIC,4HZERO,
                .            4HZZZZ,4HZZZZ,4HZZZZ,4HZZZZ,4HZZZZ/
            C
            C------------------- READ NEXT CARD ---
0012           10 READ(5,1001) CARD
0013              CALL TIME(TIM)
0014              WRITE(6,2000) CARD,TIM
0015              DO 20 I=1,20
0016              IF(CARD(1).EQ.WORD(I)) GOTO 30
0017           20 CONTINUE
0018              WRITE(6,3000)
0019              GOTO 10
            C------------------- JUMP TO APPROPRIATE CODE ---
0020           30 GOTO (100,150,200,250,300,
                .       350,400,450,500,10,
                .       600,650,700,750,800,
                .       10, 10, 10, 10, 10), I
            C
0021           40 WRITE(6,3001)
0022              GOTO 10
            C------------------- CREATE A NEW BLOCK ---
0023          100 NBLOKS=NBLOKS+1
0024              DECODE(30,1003,CARD) NC,JFIX
0025              CALL LIMIT(NVARB+3*NC)
0026              READ(5,1002) (X(I),Y(I),I=1,NC)
0027              WRITE(6,2001) (X(I),Y(I),I=1,NC)
0028              NEMPT=NEMPTG
0029              I2=NEMPT
0030              NEMPT=I2+NVARB
0031              IA(NBLOKS)=I2
0032              IA(I2+12)=NEMPT
0033              IA(I2+13)=0
0034              IF(JFIX.NE.0) IA(I2)=1
0035              IA(I2+1)=NC
            C------------------ AREA AND CENTROID OF THIS BLOCK ---
0036              AREA=(X(1)-X(NC))*(Y(1)+Y(NC))
```

```
      YC=(X(1)-X(NC))*((Y(1)-Y(NC))*(Y(1)+2.0*Y(NC))+3.0*Y(NC)**2)
      XC=(Y(1)-Y(NC))*((X(1)-X(NC))*(X(1)+2.0*X(NC))+3.0*X(NC)**2)
      DO 110 I=2,NC
      AREA=AREA+(X(I)-X(I-1))*(Y(I)+Y(I-1))
      YC=YC+(X(I)-X(I-1))*((Y(I)-Y(I-1))*(Y(I)+2.0*Y(I-1))
     .      +3.0*Y(I-1)**2)
      XC=XC+(Y(I)-Y(I-1))*((X(I)-X(I-1))*(X(I)+2.0*X(I-1))
     .      +3.0*X(I-1)**2)
  110 CONTINUE
      AREA=0.5*AREA
      YC=YC/(6.0*AREA)
      XC=-XC/(6.0*AREA)
      YC=(YC-YL)*SFACT
      XC=(XC-XL)*SFACT
      AREA=AREA*SFACT*SFACT
      A(I2+2)=XC
      A(I2+3)=YC
      A(I2+7)=AREA*RHO
C------------------- LOCAL COORDINATES FOR THIS BLOCK ---
      DO 120 I=1,NC
      A(NEMPT)=(X(I)-XL)*SFACT-XC
      A(NEMPT+1)=(Y(I)-YL)*SFACT-YC
      IA(NEMPT+2)=NEMPT+3
  120 NEMPT=NEMPT+3
      IA(NEMPT-1)=IA(I2+12)
C------------------- MOMENT OF INERTIA ---
      RMOI=0.0
      IC=IA(I2+12)
      DO 130 NP=1,NC
      IC1=IA(IC+2)
      AREA=A(IC)*A(IC+1) + (A(IC1)-A(IC))*(A(IC1+1)+A(IC+1))
     .      - A(IC1)*A(IC1+1)
      AREA=0.5*AREA
      TEMP=A(IC)**2+A(IC+1)**2+A(IC1)**2+A(IC1+1)**2
     .      +A(IC)*A(IC1)+A(IC+1)*A(IC1+1)
      RMOI=RMOI+AREA*TEMP/6.0
  130 IC=IC1
      A(I2+8)=RMOI*RHO
C
      WRITE(6,2002) A(I2+2),A(I2+3),A(I2+7),A(I2+8)
C
C------------------- GLOBAL COORDINATES ---
      IC=IA(I2+12)
      DO 140 I=1,NC
      A(IC)=A(IC)+A(I2+2)
      A(IC+1)=A(IC+1)+A(I2+3)
  140 IC=IA(IC+2)
      NEMPTG=NEMPT
      GOTO 10
C------------------- DELETE A BLOCK ---
  150 GOTO 40
C------------------- DUMP MEMORY AS REQUESTED ---
  200 DECODE(30,1003,CARD) LOC1,LOC2
      IF(LOC2.NE.0) GOTO 220
      LOC2=LOC1
      LOC1=1
```

```
      220 CALL DUMPC
          GOTO 10
C------------------- CYCLE ROUND MOTION AND FORD ---
      250 DECODE(20,1003,CARD) NCYC
          IF(MCYCLE.NE.0) GO TO 280
C----------------- DETERMINE TIMESTEP ---
          TDEL=1.0E20
          DO 260 NB1=1,NBLOKS
          I2=IA(NB1)
          TN=2.0*SQRT(A(I2+7)/STIFN)
          TS=2.0*SQRT(A(I2+7)/STIFS)
          TDEL=AMIN1(TDEL,TN,TS)
      260 CONTINUE
          TDEL=TDEL*TFRAC
          WRITE(6,3005) TDEL
          BDT=BETA/TDEL
          CON1=1.0-ALPHA*TDEL/2.0
          CON2=1.0/(1.0+ALPHA*TDEL/2.0)
C------------------- BOXING OF BLOCKS ---
          DO 270 NB1=1,NBLOKS
          CALL BOXC
      270 CONTINUE
      280 RETURN
C------------------- STOP COMMAND ---
      300 CALL FINISH
C------------------- PLOT COMMAND ---
      350 CALL BPLOTC
          GOTO 10
C------------------- RETURN TO PHASE 1 ---
      400 CALL SETUPC
          GOTO 10
C------------------- SET REAL DATA ---
      450 DECODE(30,1004,CARD) IADR,VAL
          IF(IADR.LE.0.OR.IADR.GT.M4) GOTO 480
          A(IADR)=VAL
          GOTO 10
      480 WRITE(6,3002)
          GOTO 10
C------------------- SET INTEGER DATA ---
      500 DECODE(30,1003,CARD) IADR,IVAL
          IF(IADR.LE.0.OR.IADR.GT.M7) GOTO 480
          IA(IADR)=IVAL
          GOTO 10
C------------------- GRAVITY ---
      600 DECODE(30,1005,CARD) GRAVY,GRAVX
          GOTO 10
C------------------- CONTACT STIFFNESSES ---
      650 DECODE(30,1005,CARD) STIFN,STIFS
          GO TO 10
C------------------- RAYLEIGH DAMPING ---
      700 DECODE(50,1006,CARD) FRAC,FREQ,IF1,IF2
          PI2=8.0*ATAN(1.0)
          ALPHA=PI2*FRAC*FREQ
          BETA=FRAC/(PI2*FREQ)
          IF(IF1.EQ.0) GO TO 720
          ALPHA=0.0
```

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FORTRAN IV-PLUS V02-04G          14:35:09    29-MAR-78           PAGE 8
RBMC.FTN         /I4/TR:BLOCKS/WR

           . WRITE(6,3003)
       720 IF(IF2.EQ.0) GO TO 10
            BETA=0.0
            WRITE(6,3004)
            GO TO 10
     C-------------------- FRICTION COEFFICIENT ---
       750 DECODE(20,1005,CARD) FRIC
            GOTO 10
     C-------------------- ZERO ALL VELOCITIES ---
       800 DO 820 NB=1,NBLOKS
            I2=IA(NB)
            A(I2+4)=0.0
            A(I2+5)=0.0
            A(I2+6)=0.0
       820 CONTINUE
            GOTO 10
     C
      1001 FORMAT(20A4)
      1002 FORMAT(8F10.0)
      1003 FORMAT(10X,2I10)
      1004 FORMAT(10X,I10,F10.0)
      1005 FORMAT(10X,2F10.0)
      1006 FORMAT(10X,2F10.0,2I10)
      2000 FORMAT(1X,4H+++ ,20A4,4H +++,32X,10A1)
      2001 FORMAT(1X,4(1H(,E12.4,1H,,E12.4,3H ) ))
      2002 FORMAT(18H XC,YC,MASS,RMOI :,1P4E12.3)
      3000 FORMAT(28H !!! ERROR : ILLEGAL COMMAND)
      3001 FORMAT(34H !!! ERROR : COMMAND NOT AVAILABLE)
      3002 FORMAT(33H !!! ERROR : ADDRESS OUT OF RANGE)
      3003 FORMAT(10X,29HMASS DAMPING TERM SET TO ZERO)
      3005 FORMAT(X/,30X,17H TIME INCREMENT =,1PE12.4)
      3004 FORMAT(10X,34HSTIFFNESS DAMPING TERM SET TO ZERO)
     C
            END


PROGRAM SECTIONS

 NAME        SIZE                    ATTRIBUTES

$CODE1    005314   1382              RW,I,CON,LCL
$PDATA    000056     23              RW,D,CON,LCL
$IDATA    000546    179              RW,D,CON,LCL
$VARS     001232    333              RW,D,CON,LCL
$TEMPS    000030     12              RW,D,CON,LCL
.$$$$.    027340   6000              RW,D,OVR,GBL
CBLOCK    000424    138              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 037406   8067
```

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FORTRAN IV-PLUS V02-04G          14:36:00     29-MAR-78            PAGE 9
RBMC.FTN          /14/TR:BLOCKS/WR

            SUBROUTINE BOXC
      C
      C-------------------- ROUTINE TO BOX BLOCKS ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(3000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
           .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
           .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
            LOGICAL EFLAG
            DATA TOL/1.0/
      C
            I2=IA(NB1)
            NC=IA(I2+1)
      C-------------------- DETERMINE CORNER COORDINATES ---
            IEND1=IA(I2+12)
            X1=A(IEND1)
            Y1=A(IEND1+1)
            IEND2=IA(IEND1+2)
            X2=A(IEND2)
            Y2=A(IEND2+1)
            XSTEP=1.0
            YSTEP=1.0
            NP=0
            I2N=0
      C-------------------- START BOXING ---
        150 NP=NP+1
            NS=1
            XTOL=0.0
            YTOL=0.0
      C-------------------- DETERMINE SCANNING DIRECTION ---
            IF(ABS(X2-X1).GT.ABS(Y2-Y1)) NS=0
      C-------------------- DETERMINE X AND Y INCREMENTS ---
            IF(X1.GT.X2) XSTEP=-XSTEP
            IF(Y1.GT.Y2) YSTEP=-YSTEP
      C-------------------- DETERMINE TOLERANCES ---
            IF(NS.EQ.0) XTOL=TOL*XSTEP
            IF(NS.EQ.1) YTOL=TOL*YSTEP
      C-------------------- DETERMINE LIMITS OF EDGE ---
            IBOX1=MIN0(IFIX((X1-XTOL)/BSIZE)+1,IBOXES)
            JBOX1=MIN0(IFIX((Y1-YTOL)/BSIZE),JBOXES-1)
            IBOXN=MIN0(IFIX((X2+XTOL)/BSIZE)+1,IBOXES)
            JBOXN=MIN0(IFIX((Y2+YTOL)/BSIZE),JBOXES-1)
            NBOX1=JBOX1*IBOXES+IBOX1
            NBOXN=JBOXN*IBOXES+IBOXN
      C-------------------- SET BOX POINTERS ---
            I21=M2+NBOX1-1
            I22=M2+NBOXN-1
            IF(I2N.EQ.I22) GO TO 750
            I2N=0
```

```
FORTRAN IV-PLUS V02-04G        14:36:00     29-MAR-78          PAGE 10
RBMC.FTN         /I4/TR:BLOCKS/WR

            GO TO 450
      C------------------- DETERMINE DIRECTION OF BOX INCREMENT ---
        200 IF(IBOX1.EQ.IBOXN) GO TO 650
            IF(JBOX1.EQ.JBOXN) GO TO 700
            IF(I2N.EQ.0) GO TO 210
            IF(NS.EQ.0) GO TO 650
            GO TO 700
      C------------------- SET UP EQUATION OF THE LINE ---
        210 TEMP1=(Y2-Y1)/(X2-X1)
            TEMP2=Y1-X1*TEMP1
            IF(NS.EQ.0) GO TO 250
      C------------------- DETERMINE COORDINATES OF INTERSECTION
      C                    WITH BOX GRID ---
            YN=FLOAT(JBOX1)*BSIZE
            IF(Y1.GT.Y2) YN=YN+BSIZE
            GO TO 300
        250 XN=FLOAT(IBOX1-1)*BSIZE
            IF(X1.GT.X2) XN=XN+BSIZE
        300 IF(NS.EQ.0) GO TO 350
            YN=YN+YSTEP*BSIZE
            XN=(YN-TEMP2)/TEMP1
            GO TO 400
        350 XN=XN+XSTEP*BSIZE
            YN=TEMP1*XN+TEMP2
      C------------------- DETERMINE THE BOX IN WHICH THE
      C                    INTERSECTION OCCURS ---
        400 JBOXN=MIN0(IFIX((YN+YTOL)/BSIZE),JBOXES-1)
            IBOXN=MIN0(IFIX((XN+XTOL)/BSIZE)+1,IBOXES)
            NBOXN=JBOXN*IBOXES+IBOXN
      C------------------- SET BOX POINTER ---
            I2N=M2+NBOXN-1
            GO TO 200
      C------------------- IS BLOCK ALREADY ENTERED ?---
        450 IF(IA(I21).EQ.0) GO TO 550
            I23=IA(I21)
        500 IF(ABS(IA(I23)).EQ.NB1) GO TO 600
            IF(IA(I23+1).EQ.0) GO TO 550
            I23=IA(I23+1)
            GO TO 500
      C------------------- NO, PLACE ENTRY IN EMPTY 'DOUBLES' LIST ---
        550 CALL EMPTYD
            IA(NEMPT+1)=IA(I21)
            IA(I21)=NEMPT
            IA(NEMPT)=-NB1
      C--------------------- YES ---
        600 IF(IA(I23).EQ.NB1) IA(I23)=-IA(I23)
      C------------------ IS ALL THE EDGE BOXED ?---
            IF(I21.EQ.I22) GO TO 750
            IF(I21.EQ.I2N) GO TO 300
      C------------------- NO, INCREMENT BOX NUMBER ---
            GO TO 200
      C------------------- INCREMENT IN Y DIRECTION ---
        650 I21=I21+IFIX(YSTEP)*IBOXES
            JBOX1=JBOX1+IFIX(YSTEP)
            GO TO 450
      C------------------- INCREMENT IN X DIRECTION ---
```

```
FORTRAN IV-PLUS V02-04G          14:36:00     29-MAR-78            PAGE 11
RBMC.FTN          /I4/TR:BLOCKS/WR

      700 I21=I21+IFIX(XSTEP)
          IBOX1=IBOX1+IFIX(XSTEP)
          GO TO 450
      750 XSTEP=ABS(XSTEP)
          YSTEP=ABS(YSTEP)
        C------------------- IS THE BLOCK BOXED ?---
          IF(NP.EQ.NC) GO TO 800
        C------------------- NO, BOX NEXT EDGE ---
          I2N=I22
          X1=A(IEND2)
          Y1=A(IEND2+1)
          IEND2=IA(IEND2+2)
          X2=A(IEND2)
          Y2=A(IEND2+1)
          GO TO 150
        C------------------- YES, DELETE OBSOLETE ENTRIES ---
      800 CONTINUE
          CALL DELENT
          RETURN
          END

PROGRAM SECTIONS

 NAME       SIZE                   ATTRIBUTES

$CODE1  003302   865               RW,I,CON,LCL
$IDATA  000046    19               RW,D,CON,LCL
$VARS   000160    56               RW,D,CON,LCL
$TEMPS  000004     2               RW,D,CON,LCL
.$$$$.  027340  6000               RW,D,OVR,GBL
CBLOCK  000424   138               RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 033520  7080
```

```
FORTRAN IV-PLUS V02-04G          14:36:31     29-MAR-78           PAGE 12
RBMC.FTN          /14/TR:BLOCKS/WR

              SUBROUTINE CYCLEC
        C
        C------------------- DRIVER FOR ITERATIONS ---
        C
              INCLUDE 'COMMON.FTN'
              COMMON A(3000)
              DIMENSION IA(1)
              EQUIVALENCE (A,IA)
              INCLUDE 'CBLOCK.FTN'
              COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
             .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
             .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
             .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
             .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
              LOGICAL EFLAG
        C
              DO 100 NCYCLE=1,NCYC
              MCYCLE=MCYCLE+1
        C------------------- SCAN ALL BLOCKS ---
              UDMAX=0.0
              DO 20 NB1=1,NBLOKS
              IBR=IA(NB1)
              CALL MOTIOC(A(IBR))
           20 CONTINUE
        C------------------- EXIT IF NOTHING MOVED ---
              IF(UDMAX.EQ.0) RETURN
        C------------------- CALL FORD ---
              DO 50 NB1=1,NBLOKS
           50 CALL FORDC
        C
        C------------------- CHECK FOR CRACKING ---
              DO 60 NB1=1,NBLOKS
              I2=IA(NB1)
        C------------------- FIXED BLOCKS NOT CONSIDERED ---
              IF(IA(I2).NE.0) GO TO 60
              CALL CFORCE
           60 CONTINUE
        C
        C------------------- END CYCLE LOOP ---
        C
          100 CONTINUE
        C
              RETURN
        C
              END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	000614	198	RW,I,CON,LCL
$IDATA	000006	3	RW,D,CON,LCL
$VARS	000014	6	RW,D,CON,LCL
$TEMPS	000010	4	RW,D,CON,LCL

```
FORTRAN IV-PLUS V02-04G          14:36:39     29-MAR-78            PAGE 14
RBMC.FTN          /14/TR:BLOCKS/WR

0001          SUBROUTINE MOTIOC(B)
        C
        C------------------- LAW OF MOTION FOR A SINGLE BLOCK ---
        C
0002          INCLUDE 'COMMON.FTN'
0003 *        COMMON A(3000)
0004 *        DIMENSION IA(1)
0005 *        EQUIVALENCE (A,IA)
0006          INCLUDE 'CBLOCK.FTN'
0007 *        COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *       .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *       .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *       .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *       .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *       .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *        LOGICAL EFLAG
0009          DIMENSION B(1)
0010          EQUIVALENCE (FIX,JFIX),(AIC,IC),(ANC,NC)
        C
0011          FIX=B(1)
        C------------------- IS THIS BLOCK FIXED ? ---
0012          IF(JFIX.NE.0) RETURN
        C------------------- NO ---
        C------------------- VELOCITIES FROM ACCELERATIONS ---
0013          B(5)=(B(5)*CON1+(B(10)/B(8)+GRAVX)*TDEL)*CON2
0014          B(6)=(B(6)*CON1+(B(11)/B(8)+GRAVY)*TDEL)*CON2
0015          B(7)=(B(7)*CON1+(B(12)/B(9))*TDEL)*CON2
0016          B(10)=0.0
0017          B(11)=0.0
0018          B(12)=0.0
        C------------------- UPDATE BLOCK CORNERS ---
        C
0019          AIC=B(13)
0020          ANC=B(2)
        C
0021          DO 50 NPR=2,NC+1
0022          IEND1=IC
0023          IEND2=IA(IEND1+2)
0024          XARM=A(IEND2)-B(3)
0025          YARM=A(IEND2+1)-B(4)
0026          XDC=B(5)-B(7)*YARM
0027          YDC=B(6)+B(7)*XARM
0028          UDMAX=AMAX1(UDMAX,ABS(XDC),ABS(YDC))
0029          IBX=A(IEND2)
0030          IBY=A(IEND2+1)
0031          A(IEND2)=A(IEND2)+XDC*TDEL
0032          A(IEND2+1)=A(IEND2+1)+YDC*TDEL
        C------------------- IS MOVEMENT GREATER THAN 1.0 UNITS ? ---
0033          IF(IBX.EQ.IFIX(A(IEND2)).AND.IBY.EQ.IFIX(A(IEND2+1))) GO TO 50
        C------------------- YES,CALL SCAN AND DETECT ---
0034          CALL SCAN(2)
0035          IEND1=IC
0036          CALL DETECT
        C------------------- NO,UPDATE NEXT CORNER ---
0037       50 IC=IA(IEND1+2)
        C------------------- RIGID BODY DISPLACEMENTS ---
```

```
FORTRAN IV-PLUS V02-04G          14:36:39     29-MAR-78            PAGE 15
RBMC.FTN          /I4/TR:BLOCKS/WR

0038            B(3)=B(3)+B(5)*TDEL
0039            B(4)=B(4)+B(6)*TDEL
          C-------------------------------------------------------
0040            RETURN
          C
0041            END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1  001156   311              RW,I,CON,LCL
$PDATA  000004     2              RW,D,CON,LCL
$IDATA  000030    12              RW,D,CON,LCL
$VARS   000050    20              RW,D,CON,LCL
$TEMPS  000006     3              RW,D,CON,LCL
.$$$$.  027340  6000              RW,D,OVR,GBL
CBLOCK  000424   138              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 031254  6486
```

```
      SUBROUTINE FORDC
C
C------------------- FORCE DISPLACEMENT LAW FOR SINGLE CONTACT ---
C
      INCLUDE 'COMMON.FTN'
      COMMON A(3000)
      DIMENSION IA(1)
      EQUIVALENCE (A,IA)
      INCLUDE 'CBLOCK.FTN'
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
      LOGICAL EFLAG
C
C------------------- SCAN CONTACT LIST ---
C
      IBE=IA(NB1)
   10 JC1=IA(IBE+13)
      JTEMP=IBE+13
   20 IF(JC1.EQ.0) RETURN
C-------------------  RETURN IF NO CONTACTS OR END OF LIST ---
      IC1=IA(JC1)
      NB2=IA(IC1+3)
      IF(NB1.EQ.NB2) GO TO 30
      IBC=IA(NB2)
      GO TO 40
   30 JTEMP=JC1+1
      JC1=IA(JC1+1)
      GO TO 20
C
C------------------- RELATIVE X AND Y VELOCITIES ACROSS CONTACTS ---
   40 XCC=A(IC1+10)-A(IBC+2)
      YCC=A(IC1+11)-A(IBC+3)
      XCE=A(IC1+10)-A(IBE+2)
      YCE=A(IC1+11)-A(IBE+3)
      XD=(A(IBC+4)-A(IBC+6)*YCC)-(A(IBE+4)-A(IBE+6)*YCE)
      YD=(A(IBC+5)+A(IBC+6)*XCC)-(A(IBE+5)+A(IBE+6)*XCE)
C------------------- SHEAR AND NORMAL DISPLACEMENT INCREMENTS ---
      DUS=(XD*A(IC1+9)+YD*A(IC1+8))*TDEL
      DUN=(YD*A(IC1+9)-XD*A(IC1+8))*TDEL
      A(IC1+4)=A(IC1+4)+DUS
      A(IC1+5)=A(IC1+5)+DUN
C------------------- NORMAL FORCE ---
      DFN=-DUN*STIFN
      A(IC1+6)=A(IC1+6)+DFN
C------------------- TEST FOR TENSION ---
      IF(A(IC1+6).GE.0.0) GO TO 50
      A(IC1+6)=0.0
      A(IC1+7)=0.0
      DN=0.0
      DS=0.0
C------------------- SHEAR FORCE ---
   50 DFS=DUS*STIFS
```

```
0039          A(IC1+7)=A(IC1+7)+DFS
0040          FRICF=FRIC*A(IC1+6)
0041          IF(ABS(A(IC1+7)).LE.FRICF) GO TO 60
0042          A(IC1+7)=SIGN(FRICF,A(IC1+7))
0043          DS=0.0
0044          GOTO 70
        C------------------- DASHPOT FORCES ---
0045       60 DS=BDT*DFS
0046       70 DN=BDT*DFN
        C------------------- GLOBAL CONTACT FORCES ---
0047          FYC=(A(IC1+7)+DS)*A(IC1+8)-(A(IC1+6)+DN)*A(IC1+9)
0048          FXC=(A(IC1+7)+DS)*A(IC1+9)+(A(IC1+6)+DN)*A(IC1+8)
        C------------------- ADD CONTRIBUTION TO BLOCK FORCES ---
0049          A(IBC+9)=A(IBC+9)-FXC
0050          A(IBC+10)=A(IBC+10)-FYC
0051          A(IBC+11)=A(IBC+11)-(FYC*(A(IC1+10)-A(IBC+2))-FXC*(A(IC1+11)
             .         -A(IBC+3)))
0052          A(IBE+9)=A(IBE+9)+FXC
0053          A(IBE+10)=A(IBE+10)+FYC
0054          A(IBE+11)=A(IBE+11)+(FYC*(A(IC1+10)-A(IBE+2))-FXC*(A(IC1+11)
             .         -A(IBE+3)))
        C
0055          GO TO 30
        C
0056          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001430	396	RW,I,CON,LCL
$IDATA	000006	3	RW,D,CON,LCL
$VARS	000124	42	RW,D,CON,LCL
$TEMPS	000002	1	RW,D,CON,LCL
.$$$$.	027340	6000	RW,D,OVR,GBL
CBLOCK	000424	138	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 031550   6580

```
FORTRAN IV-PLUS V02-04G        14:37:12    29-MAR-78          PAGE 18
RBMC.FTN        /I4/TR:BLOCKS/WR

0001           SUBROUTINE CFORCE
         C
         C------------------- LOCATION OF CONTACT DATA ---
         C
0002           INCLUDE 'COMMON.FTN'
0003 *         COMMON A(3000)
0004 *         DIMENSION IA(1)
0005 *         EQUIVALENCE (A,IA)
0006           INCLUDE 'CBLOCK.FTN'
0007 *         COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *        .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *        .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *        .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *        .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *        .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *         LOGICAL EFLAG
         C
0009           I2=IA(NB1)
0010           NP=0
         C------------------- SCAN CONTACT LIST ---
0011           JC1=IA(I2+13)
0012           NEMPT=NEMPTG-1
         C------------------- NO ENTRIES OR END OF LIST ?---
0013       100 IF(JC1.EQ.0) GO TO 200
0014           IC1=IA(JC1)
0015           IF(IA(IC1+3).EQ.NB1) GO TO 150
         C------------------ STORE POINTERS TO CONTACTS INVOLVING
         C                   THE CORNER OF ANOTHER BLOCK ---
0016           CALL LIMIT(1)
0017           NEMPT=NEMPT+1
0018           IA(NEMPT)=IC1
0019           NP=NP+1
         C------------------- GET NEXT CONTACT POINTER ---
0020       150 JC1=IA(JC1+1)
0021           GO TO 100
         C------------------ TEST CRACK CRITERION ---
0022       200 IF(NP.LT.2) GO TO 250
0023           CALL CRACK
0024       250 RETURN
0025           END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1   000402    129            RW,I,CON,LCL
$PDATA   000004      2            RW,D,CON,LCL
$IDATA   000006      3            RW,D,CON,LCL
$VARS    000020      8            RW,D,CON,LCL
.$$$$.   027340   6000            RW,D,OVR,GBL
CBLOCK   000424    138            RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 030420  6280
```

```
FORTRAN IV-PLUS V02-04G          14:37:18    29-MAR-78              PAGE 20
RBMC.FTN         /14/TR:BLOCKS/WR

0001           SUBROUTINE CRACK
         C
         C------------------- CRACK CRITERION ---
         C
0002           INCLUDE 'COMMON.FTN'
0003 *         COMMON A(3000)
0004 *         DIMENSION IA(1)
0005 *         EQUIVALENCE (A,IA)
0006           INCLUDE 'CBLOCK.FTN'
0007 *         COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *        .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *        .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *        .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *        .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *        .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *         LOGICAL EFLAG
         C
0009           TENS2=0.0
0010           NTEMP1=NEMPTG+1
0011           NTEMP2=NEMPTG
         C------------------- CHECK EACH POSSIBLE CRACK ---
0012           IFN2=IA(NEMPTG)
0013           IFN3=IA(NEMPTG+1)
0014           FN2=A(IFN2+6)
         C
0015       100 IF(IFN2.EQ.IFN3) GO TO 150
0016           IF(IA(IFN2+1).EQ.IA(IFN3+1)) GO TO 150
0017           FN3=A(IFN3+6)
         C------------------- CALCULATE TENSILE STRESS ---
0018           Z=(A(IFN3+10)-A(IFN2+10))**2
              . +(A(IFN3+11)-A(IFN2+11))**2
0019           IF(Z.LT.1.0) GO TO 150
0020           TENS1=(FN2+FN3)/Z
         C------------------- FIND MAXIMUM TENSILE STRESS ---
0021           TENS2=AMAX1(TENS1,TENS2)
0022           IF(TENS2.GT.TENS1) GO TO 150
         C------------------- SET POINTERS TO CONTACTS CAUSING
         C                    MAXIMUM TENSILE STRESS ---
0023           IF2=IFN2
0024           IF3=IFN3
         C
0025       150 NTEMP1=NTEMP1+1
0026           IF(NTEMP1.GT.NEMPT) GO TO 200
0027           IFN3=IA(NTEMP1)
0028           GO TO 100
         C
0029       200 NTEMP2=NTEMP2+1
0030           IF(NTEMP2.GT.NEMPT) GO TO 300
0031           IFN2=IA(NTEMP2)
0032           IFN3=IA(NEMPTG)
0033           FN2=A(IFN2+6)
0034           NTEMP1=NEMPTG
0035           GO TO 100
         C-------------------END OF CHECK ---
         C
         C-------------------IS TENSILE STRENGTH EXCEEDED ?---
```

```
FORTRAN IV-PLUS V02-04G          14:37:18    29-MAR-78          PAGE 21
RBMC.FTN         /I4/TR:BLOCKS/WR

0036        300 IF(TENS2.LT.TMAX) GO TO 400
          C------------------ YES,INTRODUCE CRACK ---
0037            CALL SPLIT(IF2,IF3)
          C------------------ NO,RETURN ---
0038        400 RETURN
0039            END

PROGRAM SECTIONS

 NAME       SIZE                 ATTRIBUTES

$CODE1  000730   236             RW,I,CON,LCL
$IDATA  000014     6             RW,D,CON,LCL
$VARS   000054    22             RW,D,CON,LCL
.$$$$.  027340  6000             RW,D,OVR,GBL
CBLOCK  000424   138             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 031004  6402
```

```
            SUBROUTINE SPLIT(IF2,IF3)
      C
      C------------------- CRACK INTRODUCED ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(3000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
          .                 NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
          .                 TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
          .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
          .                 CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
          .                 NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
            LOGICAL EFLAG
      C
            I2=IA(NB1)
            NC1=IA(I2+1)
      C------------------- SUPPRESS CRACKS TOO CLOSE TO
      C                    EXISTING CORNERS ---
            X1=A(IF2+10)
            X2=A(IF3+10)
            Y1=A(IF2+11)
            Y2=A(IF3+11)
            IPOINT=IA(I2+12)
            DO 10 I=1,NC1
            XDIF=X1-A(IPOINT)
            YDIF=Y1-A(IPOINT+1)
            Z2=XDIF*XDIF+YDIF*YDIF
            XDIF=X2-A(IPOINT)
            YDIF=Y2-A(IPOINT+1)
            Z2=AMIN1(Z2,XDIF*XDIF+YDIF*YDIF)
            IF(Z2.LT.4.0) RETURN
         10 IPOINT=IA(IPOINT+2)
      C
            WRITE(6,2001) NB1,X1,Y1,X2,Y2
      C
      C
            NBLOKS=NBLOKS+1
            IF(NBLOKS.LT.M2) GO TO 20
            WRITE(6,3000)
            EFLAG=.TRUE.
            CALL FINISH
      C
      C------------------- EDGES INVOLVED IN CRACK ---
         20 NP1=IA(IF2+1)
            NP2=IA(IF3+1)
      C------------------- IS NP2 GREATER THAN NP1 ? ---
            IF(NP2.GT.NP1) GO TO 50
      C------------------- NO, REARRANGE ---
            NTEMP=NP1
            NP1=NP2
            NP2=NTEMP
            NTEMP=IF3
            IF3=IF2
```

```
      IF2=NTEMP
   50 CONTINUE
C------------------- YES ---
      IEND1=IA(I2+12)
      DO 100 I=1,NC1
      IF(NP1.EQ.I) IC2=IEND1
      IF(NP2.EQ.I) IC3=IEND1
      IF(NP1.LE.I.AND.NP2.LE.I) GO TO 110
  100 IEND1=IA(IEND1+2)
C------------------- CREATE MEMORY FOR NEW BLOCK DATA ---
  110 NBN=NBLOKS
      CALL LIMIT(NVARB+12)
      IA(NBN)=NEMPTG
      NEMPTG=NEMPTG+NVARB
C------------------- DETERMINE CORNER COORDINATES OF NEW BLOCKS ---
      IC22=IA(IC2+2)
      IC33=IA(IC3+2)
C------------------- FOR BLOCK NB1 ---
      IA(IC2+2)=NEMPTG
      A(NEMPTG)=A(IF2+10)
      A(NEMPTG+1)=A(IF2+11)
      IA(NEMPTG+2)=NEMPTG+3
      A(NEMPTG+3)=A(IF3+10)
      A(NEMPTG+4)=A(IF3+11)
      IA(NEMPTG+5)=IA(IC3+2)
      NEMPTG=NEMPTG+6
C------------------- FOR BLOCK NBN ---
      IA(IC3+2)=NEMPTG
      A(NEMPTG)=A(IF3+10)
      A(NEMPTG+1)=A(IF3+11)
      IA(NEMPTG+2)=NEMPTG+3
      A(NEMPTG+3)=A(IF2+10)
      A(NEMPTG+4)=A(IF2+11)
      IA(NEMPTG+5)=IC22
      NEMPTG=NEMPTG+6
C------------------- CREATE NEW BLOCK DATA---
      NP=0
      I21=IA(NB1)
  115 NP=NP+1
      NC=0
      IEND1=IA(I2+12)
C------------------- NUMBER OF CORNERS ? ---
  120 NC=NC+1
      IEND1=IA(IEND1+2)
      IF(IEND1.EQ.IA(I2+12)) GO TO 125
      GO TO 120
  125 IA(I2)=0
      IA(I2+1)=NC
C------------------- AREA AND CENTROID  ---
      AREA=0.0
      XC=0.0
      YC=0.0
      IEND1=IA(I2+12)
      DO 130 I=1,NC
      IEND2=IA(IEND1+2)
      AREA=AREA+(A(IEND2)-A(IEND1))*(A(IEND2+1)+A(IEND1+1))
```

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FORTRAN IV-PLUS V02-04G          14:37:31     29-MAR-78            PAGE 24
RBMC.FTN          /14/TR:BLOCKS/WR

            YC=YC+(A(IEND2)-A(IEND1))*((A(IEND2+1)-A(IEND1+1))*(A(IEND2+1)
     .         +2.0*A(IEND1+1))+3.0*A(IEND1+1)**2)
            XC=XC+(A(IEND2+1)-A(IEND1+1))*((A(IEND2)-A(IEND1))*(A(IEND2)
     .         +2.0*A(IEND1))+3.0*A(IEND1)**2)
            IEND1=IEND2
      130 CONTINUE
            AREA=0.5*AREA
      135 YC=YC/(6.0*AREA)
            XC=-XC/(6.0*AREA)
            YC=(YC-YL)*SFACT
            XC=(XC-XL)*SFACT
            AREA=AREA*SFACT*SFACT
            A(I2+2)=XC
            A(I2+3)=YC
            A(I2+7)=AREA*RHO
            A(I2+4)=0.0
            A(I2+5)=0.0
            A(I2+6)=0.0
            A(I2+9)=0.0
            A(I2+10)=0.0
            A(I2+11)=0.0
C------------------- LOCAL COORDINATES  ---
            IEND1=IA(I2+12)
            DO 140 I=1,NC
            A(IEND1)=(A(IEND1)-XL)*SFACT-XC
            A(IEND1+1)=(A(IEND1+1)-YL)*SFACT-YC
      140 IEND1=IA(IEND1+2)
C------------------- MOMENT OF INERTIA ---
            RMOI=0.0
            IEND1=IA(I2+12)
            DO 150 I=1,NC
C
            IEND2=IA(IEND1+2)
            AREA=A(IEND1)*A(IEND1+1) + (A(IEND2)-A(IEND1))*(A(IEND2+1)
     .         +A(IEND1+1))-A(IEND2)*A(IEND2+1)
            AREA=0.5*AREA
            TEMP=A(IEND1)**2+A(IEND1+1)**2+A(IEND2)**2+A(IEND2+1)**2
     .         +A(IEND1)*A(IEND2)+A(IEND1+1)*A(IEND2+1)
            RMOI=RMOI+AREA*TEMP/6.0
      150 IEND1=IEND2
            A(I2+8)=RMOI*RHO
C
C------------------- GLOBAL COORDINATES ---
            IEND1=IA(I2+12)
            DO 160 I=1,NC
            A(IEND1)=A(IEND1)+A(I2+2)
            A(IEND1+1)=A(IEND1+1)+A(I2+3)
      160 IEND1=IA(IEND1+2)
C
            IF(NP.EQ.2) GO TO 180
            I2=IA(NBN)
            IA(I2+12)=IC22
            GO TO 115
C------------------- DELETION OF CONTACTS CAUSING THE CRACK ---
      180 I21=IA(NB1)
            JTEMP=I21+13
```

```
FORTRAN IV-PLUS V02-04G        14:37:31     29-MAR-78            PAGE 25
RBMC.FTN          /14/TR:BLOCKS/WR

            JC1=IA(JTEMP)
        190 IF(JC1.EQ.0) GO TO 200
            IC1=IA(JC1)
            IF(IC1.NE.IF2.AND.IC1.NE.IF3) GOTO 195
            CALL DELCON(JTEMP)
            GOTO 198
        195 JTEMP=JC1+1
        198 JC1=IA(JTEMP)
            GOTO 190
      C------------------ REARRANGEMENT OF CONTACT DATA ---
        200 I2N=IA(NBN)
            XT1=(A(IF2+10)-A(IC2))*A(IF2+9)
          .    +(A(IF2+11)-A(IC2+1))*A(IF2+8)
            XT2=(A(IF3+10)-A(IC3))*A(IF3+9)
          .    +(A(IF3+11)-A(IC3+1))*A(IF3+8)
      C
            JC1=IA(I21+13)
            JTEMP=I21+13
        210 IF(JC1.EQ.0) GO TO 700
            IC1=IA(JC1)
            IF(IA(IC1+3).EQ.NB1) GO TO 220
            IF(IA(IC1+1).LT.NP1) GO TO 600
            IF(IA(IC1+1).GT.NP2) GO TO 300
      C
            GO TO 350
      C
        220 IF(IA(IC1+2).LE.NP1) GO TO 600
            IF(IA(IC1+2).LE.NP2) GO TO 250
      C
            NP3=NP2+1
            NP4=NP1+3
        230 IF(IA(IC1+2).NE.NP3) GO TO 240
            IA(IC1+2)=NP4
            GO TO 600
        240 NP3=NP3+1
            NP4=NP4+1
            GO TO 230
      C
        250 NP3=NP1+1
            NP4=1
        260 IF(IA(IC1+2).NE.NP3) GO TO 270
            IA(IC1+3)=NBN
            IA(IC1+2)=NP4
            IA(JTEMP)=IA(JC1+1)
            IA(JC1+1)=IA(I2N+13)
            IA(I2N+13)=JC1
            GO TO 600
        270 NP3=NP3+1
            NP4=NP4+1
            GO TO 260
      C
        300 NP3=NP2+1
            NP4=NP1+3
        310 IF(IA(IC1+1).NE.NP3) GO TO 320
            IA(IC1+1)=NP4
            GO TO 600
```

```
       320 NP3=NP3+1
           NP4=NP4+1
           GO TO 310
     C
       350 IF(IA(IC1+1).EQ.NP1) GO TO 380
           IF(IA(IC1+1).EQ.NP2) GO TO 400
           GO TO 500
       380 XT=(A(IC1+10)-A(IC2))*A(IC1+9)
         .  +(A(IC1+11)-A(IC2+1))*A(IC1+8)
           IF(XT.LT.XT1) GO TO 600
           IA(IC1+1)=IA(I2N+1)
           IA(JTEMP)=IA(JC1+1)
           IA(JC1+1)=IA(I2N+13)
           IA(I2N+13)=JC1
           GO TO 600
     C
       400 XT=(A(IC1+10)-A(IC3))*A(IC1+9)
         .  +(A(IC1+11)-A(IC3+1))*A(IC1+8)
           IF(XT.GT.XT2) GO TO 410
           IA(JTEMP)=IA(JC1+1)
           IA(IC1+1)=IA(I2N+1)-2
           IA(JC1+1)=IA(I2N+13)
           IA(I2N+13)=JC1
           GO TO 420
       410 IA(IC1+1)=NP1+2
       420 GO TO 600
     C
       500 NP3=NP1+1
           NP4=1
       510 IF(IA(IC1+1).NE.NP3) GO TO 520
           IA(IC1+1)=NP4
           IA(JTEMP)=IA(JC1+1)
           IA(JC1+1)=IA(I2N+13)
           IA(I2N+13)=JC1
           GO TO 600
       520 NP3=NP3+1
           NP4=NP4+1
           GO TO 510
       600 JTEMP=JC1+1
           JC1=IA(JC1+1)
           GO TO 210
     C------------------- BOXING OF NEW BLOCKS ---
       700 NP=0
           TEMP=TDEL
       710 NP=NP+1
           I2=IA(NB1)
           CALL BOXC
     C------------------- CHECK TIMESTEP ---
           TN=2.0*(SQRT(A(I2+7)/STIFN))*TFRAC
           TS=2.0*(SQRT(A(I2+7)/STIFS))*TFRAC
           TDEL=AMIN1(TDEL,TN,TS)
           IF(NP.GT.1) GO TO 720
           NTEMP=NB1
           NB1=NBN
           GO TO 710
       720 NB1=NTEMP
```

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FORTRAN IV-PLUS V02-04G         14:37:31    29-MAR-78           PAGE 27
RBMC.FTN         /14/TR:BLOCKS/WR

            IF(TDEL.EQ.TEMP) GO TO 750
            BDT=BDT*TEMP/TDEL
            CON1=1.0-ALPHA*TDEL/2.0
            CON2=1.0/(1.0+ALPHA*TDEL/2.0)
            WRITE(6,2000) TDEL
      750   RETURN
     2000   FORMAT(X/,30X,20HNEW TIME INCREMENT =,1PE12.4)
     2001   FORMAT(30X,5HBLOCK,I5,24H HAS CRACKED AT LOCATION,
          .        2E11.4,2X,2E11.4)
     3000   FORMAT(46H !!! ERROR : MAXIMUM NUMBER OF BLOCKS EXCEEDED)
            END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1   010164  2106             RW,I,CON,LCL
$IDATA   000232    77             RW,D,CON,LCL
$VARS    000234    78             RW,D,CON,LCL
$TEMPS   000010     4             RW,D,CON,LCL
.$$$$.   027340  6000             RW,D,OVR,GBL
CBLOCK   000424   138             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 040646  8403
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FORTRAN IV-PLUS V02-04G        14:39:29    29-MAR-78           PAGE 28
RBMC.FTN         /14/TR:BLOCKS/WR

              SUBROUTINE DUMPC
        C
        C------------------- ROUTINE TO PRINT MEMORY ALLOCATION AND CONTENTS -
        C
              INCLUDE 'COMMON.FTN'
              COMMON A(3000)
              DIMENSION IA(1)
              EQUIVALENCE (A,IA)
              INCLUDE 'CBLOCK.FTN'
              COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
             .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
             .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
             .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
             .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
              LOGICAL EFLAG
        C
              IF(LOC2.EQ.0) RETURN
              WRITE(6,2000)
              WRITE(6,2005) M1,M2,M3,NEMPTG,NEMPTC,NEMPTD,NBLOKS,
             .              NCYC,NEMPT,MCYCLE
              IF(LOC2.LT.0) GOTO 100
        C------------------- DUMP CONSECUTIVE MEMORY LOCATIONS ---
              WRITE(6,2009)
              I2=((LOC1-1)/10)*10
           10 I1=I2+1
              I2=I1+9
              WRITE(6,2001) (IA(I),I=I1,I2),I2
              IF(I2.LT.LOC2) GOTO 10
              GOTO 500
        C
        C------------------- DUMP BY BOX ---
          100 WRITE(6,2002)
              DO 120 NBOX=1,NBOXES
              I3=IA(M2+NBOX-1)
        C------------------- ANY MORE ENTRIES ? ---
          110 IF(I3.EQ.0) GOTO 120
        C------------------- NO, PRINT BOX,BLOCK ---
              WRITE(6,2008) NBOX,IA(I3)
              I3=IA(I3+1)
              GOTO 110
          120 CONTINUE
        C------------------- CONTENTS OF EACH BLOCK ---
              WRITE(6,2006)
              DO 130 NB=1,NBLOKS
              IF=IA(NB)
              NC=IA(IF+1)
              IL=IA(IF+12)
              CALL LIMIT(2*NC)
              DO 125 IC=NEMPTG,NEMPTG+2*NC,2
              A(IC)=A(IL)
              A(IC+1)=A(IL+1)
          125 IL=IA(IL+2)
              WRITE(6,2003) NB,IA(IF),IA(IF+1),(A(I),I=IF+2,IF+11),
             .      (A(J),J=NEMPTG,NEMPTG+2*NC-1)
          130 CONTINUE
```

```
C------------------- DUMP CONTACT DATA ---
      WRITE(6,2007)
      DO 150 NB=1,NBLOKS
      IF=IA(NB)
      JC1=IA(IF+13)
  135 IF(JC1.EQ.0) GO TO 150
      IC1=IA(JC1)
      IF(NB.EQ.IA(IC1+3)) GO TO 140
      WRITE(6,2004) NB,(IA(I),I=IC1,IC1+3),
     .                 (A(J),J=IC1+4,IC1+11)
  140 JC1=IA(JC1+1)
      GO TO 135
  150 CONTINUE
C-------------------
  500 WRITE(6,2000)
C
      RETURN
C
 2000 FORMAT(1X,130(1H-))
 2001 FORMAT(1X,10I12,I6)
 2002 FORMAT(10X,3HBOX,7X,5HBLOCK)
 2003 FORMAT(/1X,3I3,1P10E10.2/(10X,1P10E10.2))
 2004 FORMAT(/1X,5I10/1X,1P8E10.2)
 2005 FORMAT(9X,2HM1,8X,2HM2,8X,2HM3,4X,6HNEMPTG,4X,6HNEMPTC,
     .        4X,6HNEMPTD,4X,6HNBLOKS,6X,4HNCYC,5X,5HNEMPT,4X,6HMCYCLE/
     .        1X,11I10)
 2006 FORMAT(11H BLOCK DATA,10(1H-)/1X,9H NB IF NC,8X,2HXC,8X,2HYC,
     .        6X,4HXDOT,6X,4HYDOT,6X,4HTDOT,6X,4HMASS,3X,7HINERTIA,
     .        5X,5HXFSUM,5X,5HYFSUM,6X,4HMSUM)
 2007 FORMAT(13H CONTACT DATA,10(1H-)/8X,3HNBE,7X,3HPRE,7X,3HNPE,7X,
     .        3HNPC,7X,3HNBC/10X,1HS,9X,1HN,8X,2HFN,8X,2HFS,
     .        7X,3HSIN,7X,3HCOS,7X,3HXCP,7X,3HYCP)
 2008 FORMAT(1X,3I12)
 2009 FORMAT(1X,30(1H*),19HVALUES ARE INTEGERS,30(1H*))
C
      END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	002714	742	RW,I,CON,LCL
$PDATA	000004	2	RW,D,CON,LCL
$IDATA	000660	216	RW,D,CON,LCL
$VARS	000064	26	RW,D,CON,LCL
$TEMPS	000022	9	RW,D,CON,LCL
.$$$$.	027340	6000	RW,D,OVR,GBL
CBLOCK	000424	138	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 033672 7133

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FORTRAN IV-PLUS V02-04G          14:40:19     29-MAR-78            PAGE 30
RBMC.FTN        /14/TR:BLOCKS/WR

              SUBROUTINE DETECT
        C
        C------------------- ROUTINE TO DETECT AND UPDATE CONTACTS ---
        C
              INCLUDE 'COMMON.FTN'
              COMMON A(3000)
              DIMENSION IA(1)
              EQUIVALENCE (A,IA)
              INCLUDE 'CBLOCK.FTN'
              COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
             .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
             .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
             .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
             .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
             .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
              LOGICAL EFLAG
              LOGICAL FIRST
              DATA TOL/1.0/
        C
              I21=IA(NB1)
              NC1=IA(I21+1)
        C
        C------------------- CORNER COORDINATES ---
              X1=A(IEND1)
              Y1=A(IEND1+1)
              IEND2=IA(IEND1+2)
              X2=A(IEND2)
              Y2=A(IEND2+1)
              IEND3=IA(IEND2+2)
              NP=0
        C------------------- START DETECTION ---
          100 NP=NP+1
              FIRST=.TRUE.
        C------------------- EDGE NUMBER ---
              NP1=NPR+NP-2
              IF(NP1.GT.NC1) NP1=NP1-NC1
        C
        C------------------- DETERMINE LIMITS OF SCAN ---
          200 XX1=AMIN1(X1,X2)
              XX2=AMAX1(X1,X2)
              YY1=AMIN1(Y1,Y2)
              YY2=AMAX1(Y1,Y2)
        C------------------- DETERMINE BOXES TO BE SCANNED ---
              NXL=IFIX((XX1-TOL)/BSIZE)+1
              NXU=MIN0(IFIX((XX2+TOL)/BSIZE)+1,IBOXES)
              NYL=IFIX((YY1-TOL)/BSIZE)+1
              NYU=MIN0(IFIX((YY2+TOL)/BSIZE)+1,JBOXES)
        C------------------- SEARCH BOXES ---
              DO 350 JBOX=NYL,NYU
              NBOX1=(JBOX-1)*IBOXES+NXL-1
        C
              DO 300 IBOX=NXL,NXU
              NBOX1=NBOX1+1
        C------------------- SET BOX POINTER ---
              I3=M2+NBOX1-1
        C------------------- IS BOX EMPTY ?---
```

```
      IF(IA(I3).EQ.0) GO TO 300
      I31=IA(I3)
C------------------- IS ENTRY FOR ANOTHER BLOCK ?---
  210 IF(IA(I31).NE.NB1) GO TO 240
C------------------- NO,ANY MORE ENTRIES ?---
  215 IF(IA(I31+1).EQ.0) GO TO 300
C------------------- YES ---
      I31=IA(I31+1)
      GO TO 210
C
C----------------- SET UP DATA FOR SECOND BLOCK ---
  240 NB2=IA(I31)
      I22=IA(NB2)
      NC2=IA(I22+1)
      IC2=IA(I22+12)
      IC=IC2
      NC=0
C------------------- CHECK POSSIBLE CONTACT ---
  250 NC=NC+1
      IF(NC.GT.NC2) GO TO 215
C------------------- EDGE TO CORNER CONTACT ?---
      IF(NP.GT.2) GO TO 251
C------------------- NO, SCAN EDGES OF SECOND BLOCK ---
C------------------- YES, SCAN CORNERS OF SECOND BLOCK ---
      NP2=NC+1
      IF(NP2.GT.NC2) NP2=NP2-NC2
      ICL=IC2
      IC2=IA(ICL+2)
      ICR=IA(IC2+2)
      X=A(IC2)
      Y=A(IC2+1)
      IBOX2=MIN0(IFIX(X/BSIZE)+1,IBOXES)
      JBOX2=MIN0(IFIX(Y/BSIZE),JBOXES-1)
      NBOX2=JBOX2*IBOXES+IBOX2
C------------------- IS CORNER IN SAME BOX AS EDGE ?
      IF(NBOX1.EQ.NBOX2) GO TO 255
C------------------- YES, CHECK CONTACT CONDITION ---
C------------------- NO, GET NEXT CORNER ---
      GO TO 250
C------------------- CORNER TO EDGE CONTACT ---
  251 FIRST=.TRUE.
      NP1=NC
      NP2=NPR
      IF(NP2.GT.NC1) NP2=NP2-NC1
      NB2=NB1
      X1=A(IC)
      Y1=A(IC+1)
      IC=IA(IC+2)
      X2=A(IC)
      Y2=A(IC+1)
      IC2=IEND2
C------------------- NORMAL EDGE TO CORNER CONTACT TEST ---
  255 IF(.NOT.FIRST) GO TO 260
      XDIF=X2-X1
      YDIF=Y2-Y1
      Z=SQRT(XDIF**2+YDIF**2)
```

```
0079          SINA=YDIF/Z
0080          COSA=XDIF/Z
0081          FIRST=.FALSE.
        C
0082      260 YT= (A(IC2+1)-Y1)*COSA
         .     -(A(IC2)-X1)*SINA
0083          IF(YT.GT.2.0) GO TO 250
0084          IF(YT.LT.-3.0) GO TO 250
        C
0085          XT= (A(IC2)-X1)*COSA
         .     +(A(IC2+1)-Y1)*SINA
0086          IF(XT.GT.Z+2.0) GO TO 250
0087          IF(XT.LT.-2.0) GO TO 250
0088          IPFLG=1
0089          IF(YT.GT.1.0.OR.XT.GT.Z.OR.XT.LT.0.0) IPFLG=0
        C------------------- IS CONTACT ALREADY DETECTED ? ---
0090          JC1=IA(I21+13)
        C-------------------- CHECK CONTACT LIST FOR THIS BLOCK ---
0091      265 IF(JC1.EQ.0) GO TO 280
0092          IC1=IA(JC1)
        C------------------- CHECK EACH STORED CONTACT ---
0093          IF(IA(IC1+3).EQ.NB2.AND.IA(IC1+2).EQ.NP2.
         .     AND.IA(IC1+1).EQ.NP1) GO TO 270
0094          JC1=IA(JC1+1)
0095          GO TO 265
        C
0096      270 CONTINUE
        C
0097          IF(YT.GT.-2.0) GO TO 275
0098          WRITE(6,3000)
        C
        C------------------- UPDATE EXISTING CONTACT DATA ---
0099      275 A(IC1+8)=SINA
0100          A(IC1+9)=COSA
0101          A(IC1+10)=A(IC2)
0102          A(IC1+11)=A(IC2+1)
0103          IA(IC1)=IPFLG
        C
0104          IF(NP.GT.2) GO TO 400
0105          GO TO 250
        C
0106      280 CONTINUE
        C
0107          IF(IPFLG.EQ.0) GOTO 250
0108          IF(YT.GT.0.0) GO TO 250
        C
0109          YTR=(A(ICR+1)-Y1)*COSA-(A(ICR)-X1)*SINA
0110          IF(YTR.LE.-2.0) GO TO 250
        C
0111          YTL=(A(ICL+1)-Y1)*COSA-(A(ICL)-X1)*SINA
0112          IF(YTL.LE.-2.0) GO TO 250
        C
        C------------------- LOCATE EMPTY CONTACT DATA SPACE ---
0113          CALL EMPTYC
0114          IC1=NEMPT
        C------------------- LOCATE EMPTY CONTACT LIST 'DOUBLES' ---
```

```
      CALL EMPTYD
C------------------- ENTER CONTACT INTO THE CONTACT LIST  ---
      IA(NEMPT+1)=IA(I21+13)
      IA(I21+13)=NEMPT
      IA(NEMPT)=IC1
C------------------ REPEAT FOR SECOND BLOCK ---
      CALL EMPTYD
      IA(NEMPT+1)=IA(I22+13)
      IA(I22+13)=NEMPT
      IA(NEMPT)=IC1
C------------------- NEW CONTACT DATA ---
      A(IC1+4)=0.0
      A(IC1+5)=0.0
      A(IC1+6)=0.0
      A(IC1+7)=0.0
      IA(IC1+1)=NP1
      IA(IC1+2)=NP2
      IA(IC1+3)=NB2
      GO TO 275
  300 CONTINUE
  350 CONTINUE
C------------------- END SCAN OF BOXES ---
      IF(NP.GT.1) GO TO 400
      X1=X2
      Y1=Y2
      X2=A(IEND3)
      Y2=A(IEND3+1)
      GO TO 100
C------------------- CHECK ON CORNER TO EDGE CONTACT ? ---
  400 NP=NP+1
      IF(NP.GT.3) GO TO 500
C------------------ NO , END DETECTION ---
C------------------ YES, RETURN TO SCANNING LOGIC ---
      X1=A(IEND2)
      Y1=A(IEND2+1)
      X2=X1
      Y2=Y1
      ICR=IEND1
      ICL=IEND3
      GO TO 200
C
C------------------ END DETECTION ---
  500 NUPDAT=NUPDAT+1
      UMOST=0.0
C------------------- SCAN CONTACTS AGAIN TO
C                    DELETE CONTACTS NOT
C                    FLAGGED FOR PRESERVATION ---
      DO 650 NBB=1,NBLOKS
      IBE=IA(NBB)
  610 JC1=IA(IBE+13)
      JTEMP=IBE+13
  620 IF(JC1.EQ.0) GOTO 650
      IC1=IA(JC1)
      IF(NBB.EQ.IA(IC1+3)) GOTO 630
      IF(IA(IC1).NE.0) GOTO 630
      CALL DELCON(JTEMP)
```

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FORTRAN IV-PLUS V02-04G          14:40:19     29-MAR-78            PAGE 34
RBMC.FTN          /I4/TR:BLOCKS/WR

0159              GOTO 610
0160         630 JTEMP=JC1+1
0161              JC1=IA(JTEMP)
0162              GOTO 620
0163         650 CONTINUE
          C
0164        3000 FORMAT(30X,26H DRIFT CORRECTION REQUIRED)
0165              END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1  005250  1364              RW,I,CON,LCL
$IDATA  000112    37              RW,D,CON,LCL
$VARS   000330   108              RW,D,CON,LCL
$TEMPS  000014     6              RW,D,CON,LCL
.$$$$.  027340  6000              RW,D,OVR,GBL
CBLOCK  000424   138              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 035712  7653
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```
      C
            SUBROUTINE DELENT
      C
      C-------------------- DELETION OF OBSOLETE BOX ENTRIES ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(3000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
           .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
           .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
            LOGICAL EFLAG
            DATA TOL/5.0/
      C
            I2=IA(NB1)
            NC=IA(I2+1)
            NP=0
      C-------------------- DETERMINE LIMITS OF BLOCK ---
            XX1=XU
            XX2=XL
            YY1=YU
            YY2=YL
            IEND2=IA(I2+12)
        100 NP=NP+1
            X1=A(IEND2)
            Y1=A(IEND2+1)
            IEND2=IA(IEND2+2)
            XX1=AMIN1(XX1,X1)
            XX2=AMAX1(XX2,X1)
            YY1=AMIN1(YY1,Y1)
            YY2=AMAX1(YY2,Y1)
            IF(NP.EQ.NC) GO TO 150
            GO TO 100
      C-------------------- DETERMINE BOXES TO BE SEARCHED ---
        150 NXL=MAX0(IFIX((XX1-TOL)/BSIZE),1)
            NXU=MIN0(IFIX((XX2+TOL)/BSIZE)+2,IBOXES)
            NYL=MAX0(IFIX((YY1-TOL)/BSIZE),1)
            NYU=MIN0(IFIX((YY2+TOL)/BSIZE)+2,JBOXES)
      C------------------ SEARCH BOXES ---
            DO 500 JBOX=NYL,NYU
            NBOX1=(JBOX-1)*IBOXES+NXL-1
      C
            DO 400 IBOX=NXL,NXU
            NBOX1=NBOX1+1
      C
      C-------------------- SET BOX POINTER ---
            I3=M2+NBOX1-1
            JTEMP=I3
            I3=IA(I3)
      C-------------------- NO ENTRIES OR END OF LIST ?---
        200 IF(I3.EQ.0) GO TO 400
```

```
FORTRAN IV-PLUS V02-04G          14:41:37    29-MAR-78            PAGE 36
RBMC.FTN         /I4/TR:BLOCKS/WR

        C------------------- NO,IS ENTRY FOR THE BLOCK CONCERNED ?---
0040          IF(ABS(IA(I3)).NE.NB1) GO TO 250
        C------------------- YES,IS ENTRY VALID ?---
        C------------------- NO,DELETE ---
0041          IF(IA(I3).EQ.NB1) GO TO 300
        C------------------- YES,PRESERVE ---
0042          IF(IA(I3).EQ.-NB1) IA(I3)=-IA(I3)
        C------------------- GET NEXT BOX ENTRY ---
0043      250 JTEMP=I3+1
0044          I3=IA(I3+1)
0045          GO TO 200
        C------------------- DELETION OF OBSOLETE ENTRY ---
0046      300 IA(JTEMP)=IA(I3+1)
        C------------------- RECOVERY OF EMPTY 'DOUBLE' ---
0047          IF(NEMPTD.NE.0) GO TO 350
0048          NEMPTD=I3
0049          IA(NEMPTD)=0
0050          GO TO 400
0051      350 IA(I3)=NEMPTD
0052          NEMPTD=I3
0053      400 CONTINUE
0054      500 CONTINUE
        C------------------- END OF BOX SEARCH ---
0055          RETURN
0056          END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001726	491	RW,I,CON,LCL
$PDATA	000004	2	RW,D,CON,LCL
$IDATA	000060	24	RW,D,CON,LCL
$VARS	000120	40	RW,D,CON,LCL
$TEMPS	000010	4	RW,D,CON,LCL
.$$$$.	027340	6000	RW,D,OVR,GBL
CBLOCK	000424	138	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 032126   6699

```
FORTRAN IV-PLUS V02-04G          14:42:00     29-MAR-78            PAGE 37
RBMC.FTN          /I4/TR:BLOCKS/WR


            SUBROUTINE DELCON(JTEMP)
      C
      C------------------- DELETION OF OBSOLETE CONTACTS ---
      C
            INCLUDE 'COMMON.FTN'
            COMMON A(3000)
            DIMENSION IA(1)
            EQUIVALENCE (A,IA)
            INCLUDE 'CBLOCK.FTN'
            COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
           .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
           .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
           .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
           .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
           .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
            LOGICAL EFLAG
      C
      C-------------------- POINTER TO OBSOLETE DOUBLE ---
            JC1=IA(JTEMP)
      C------------------- POINTER TO OBSOLETE CONTACT DATA ---
            IC1=IA(JC1)
      C------------------- REMOVE FROM CONTACT LIST ---
            IA(JTEMP)=IA(JC1+1)
      C-------------------- RECOVER EMPTY 'DOUBLE' ---
            IA(JC1)=NEMPTD
            NEMPTD=JC1
      C-------------------- LOCATE CONTACT POINTER FROM SECOND BLOCK ---
         30 NB2=IA(IC1+3)
            I22=IA(NB2)
            JTEMP2=I22+13
            JC2=IA(JTEMP2)
      C-------------------IS THIS THE CORRECT POINTER ?---
         40 IF(IA(JC2).NE.IC1) GO TO 50
      C-------------------- YES,DELETE ENTRY,RECOVER EMPTY 'DOUBLE' ---
            IA(JTEMP2)=IA(JC2+1)
            IA(JC2)=NEMPTD
            NEMPTD=JC2
            GO TO 60
      C-------------------- NO,GET NEXT CONTACT POINTER ---
         50 JTEMP2=JC2+1
            JC2=IA(JTEMP2)
            GO TO 40
      C------------------- DELETION OF CONTACT DATA, RECOVERY OF SPACE ---
         60 IA(IC1)=NEMPTC
            NEMPTC=IC1
      C
         80 RETURN
            END


PROGRAM SECTIONS

 NAME       SIZE                 ATTRIBUTES

$CODE1   000516    167           RW,I,CON,LCL
```

```
C
      SUBROUTINE EMPTYC
C
C------------------- ROUTINE TO LOCATE EMPTY CONTACT DATA SPACE ---
C
      INCLUDE 'COMMON.FTN'
      COMMON A(3000)
      DIMENSION IA(1)
      EQUIVALENCE (A,IA)
      INCLUDE 'CBLOCK.FTN'
      COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
      LOGICAL EFLAG
C
C------------------- DOES LIST OF EMPTY CONTACT DATA EXIST ?---
      IF(NEMPTC.NE.0) GO TO 10
C------------------- NO ---
      CALL LIMIT(12)
      NEMPT=NEMPTG
      NEMPTG=NEMPTG+12
      GO TO 20
C------------------- YES ---
   10 NEMPT=NEMPTC
      NEMPTC=IA(NEMPTC)
C
   20 RETURN
C
      END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	000144	50	RW,I,CON,LCL
$PDATA	000004	2	RW,D,CON,LCL
$IDATA	000004	2	RW,D,CON,LCL
.$$$$.	027340	6000	RW,D,OVR,GBL
CBLOCK	000424	138	RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 030140 6192

NO FPP INSTRUCTIONS GENERATED

```
FORTRAN IV-PLUS V02-04G          14:42:14     29-MAR-78            PAGE 40
RBMC.FTN          /14/TR:BLOCKS/WR

0001            SUBROUTINE EMPTYD
        C
        C------------------- ROUTINE TO LOCATE EMPYTY 'DOUBLES' ---
        C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(3000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *         .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *         .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *         .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *         .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *          LOGICAL EFLAG
        C
        C------------------- DOES LIST OF EMPTY 'DOUBLES' EXIST ?---
0009            IF(NEMPTD.NE.0) GO TO 10
        C------------------ NO ---
0010            CALL LIMIT(2)
0011            NEMPT=NEMPTG
0012            NEMPTG=NEMPTG+2
0013            GO TO 20
        C------------------ YES ---
0014         10 NEMPT=NEMPTD
0015            NEMPTD=IA(NEMPTD)
        C
0016         20 RETURN
        C
0017            END

PROGRAM SECTIONS

 NAME        SIZE                    ATTRIBUTES

$CODE1  000144    50                 RW,I,CON,LCL
$PDATA  000004     2                 RW,D,CON,LCL
$IDATA  000004     2                 RW,D,CON,LCL
.$$$$.  027340  6000                 RW,D,OVR,GBL
CBLOCK  000424   138                 RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 030140   6192

NO FPP INSTRUCTIONS GENERATED
```

```
FORTRAN IV-PLUS V02-04G         14:42:18    29-MAR-78           PAGE 41
RBMC.FTN          /I4/TR:BLOCKS/WR

0001            SUBROUTINE SCAN(NC)
          C
          C------------------- ROUTINE TO CHECK BOX ENTRIES ALONG
          C                    THE EDGE OF A BLOCK ---
          C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(3000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *        .                 NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *        .                 TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *        .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *        .                 CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *        .                 NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *          LOGICAL EFLAG
0009            DATA TOL/1.0/
          C
0010            I2=IA(NB1)
          C------------------- DETERMINE COORDINATES OF THE ENDS OF
          C                    THE EDGE ---
0011            X1=A(IEND1)
0012            Y1=A(IEND1+1)
0013            IEND2=IA(IEND1+2)
0014            X2=A(IEND2)
0015            Y2=A(IEND2+1)
          C------------------- IS THE BLOCK FIXED ?---
0016            IF(X2.GT.XL.AND.X2.LT.XU.
              .    AND.Y2.GT.YL.AND.Y2.LT.YU) GO TO 100
          C------------------- YES, SET FIXED FLAG ---
0017            IA(I2)=2
0018            A(I2+4)=0.0
0019            A(I2+5)=0.0
0020            A(I2+6)=0.0
0021            RETURN
          C------------------- NO, CONTINUE ---
0022        100 XSTEP=1.0
0023            YSTEP=1.0
0024            NP=0
0025            I2N=0
          C------------------- START SCAN ---
0026        150 NP=NP+1
0027            NS=1
0028            XTOL=0.0
0029            YTOL=0.0
          C------------------- DETERMINE SCANNING DIRECTION ---
0030            IF(ABS(X2-X1).GT.ABS(Y2-Y1)) NS=0
          C------------------- DETERMINE X AND Y INCREMENTS ---
0031            IF(X1.GT.X2) XSTEP=-XSTEP
0032            IF(Y1.GT.Y2) YSTEP=-YSTEP
          C------------------- DETERMINE TOLERANCES ---
0033            IF(NS.EQ.0) XTOL=TOL*XSTEP
0034            IF(NS.EQ.1) YTOL=TOL*YSTEP
          C------------------- DETERMINE LIMITS OF EDGE ---
0035            IBOX1=MIN0(IFIX((X1-XTOL)/BSIZE)+1,IBOXES)
```

```
FORTRAN IV-PLUS V02-04G          14:42:18     29-MAR-78             PAGE 42
RBMC.FTN         /I4/TR:BLOCKS/WR

      JBOX1=MIN0(IFIX((Y1-YTOL)/BSIZE),JBOXES-1)
      IBOXN=MIN0(IFIX((X2+XTOL)/BSIZE)+1,IBOXES)
      JBOXN=MIN0(IFIX((Y2+YTOL)/BSIZE),JBOXES-1)
      NBOX1=JBOX1*IBOXES+IBOX1
      NBOXN=JBOXN*IBOXES+IBOXN
C------------------- SET BOX POINTERS ---
      I21=M2+NBOX1-1
      I22=M2+NBOXN-1
      IF(I2N.EQ.I22) GO TO 750
      I2N=0
      GO TO 450
C------------------- DETERMINE DIRECTION OF BOX INCREMENT ---
  200 IF(IBOX1.EQ.IBOXN) GO TO 650
      IF(JBOX1.EQ.JBOXN) GO TO 700
      IF(I2N.EQ.0) GO TO 210
      IF(NS.EQ.0) GO TO 650
      GO TO 700
C------------------- SET UP EQUATION OF LINE ---
  210 TEMP1=(Y2-Y1)/(X2-X1)
      TEMP2=Y1-X1*TEMP1
      IF(NS.EQ.0) GO TO 250
C------------------ DETERMINE COORDINATES OF INTERSECTION
C                   WITH BOX GRID ---
      YN=FLOAT(JBOX1)*BSIZE
      IF(Y1.GT.Y2) YN=YN+BSIZE
      GO TO 300
  250 XN=FLOAT(IBOX1-1)*BSIZE
      IF(X1.GT.X2) XN=XN+BSIZE
  300 IF(NS.EQ.0) GO TO 350
      YN=YN+YSTEP*BSIZE
      XN=(YN-TEMP2)/TEMP1
      GO TO 400
  350 XN=XN+XSTEP*BSIZE
      YN=TEMP1*XN+TEMP2
C------------------- DETERMINE THE BOX IN WHICH THE
C                    INTERSECTION OCCURS ---
  400 JBOXN=MIN0(IFIX((YN+YTOL)/BSIZE),JBOXES-1)
      IBOXN=MIN0(IFIX((XN+XTOL)/BSIZE)+1,IBOXES)
      NBOXN=JBOXN*IBOXES+IBOXN
C------------------ SET BOX POINTER ---
      I2N=M2+NBOXN-1
      GO TO 200
C------------------- IS BLOCK ALREADY ENTERED ?---
  450 IF(IA(I21).EQ.0) GO TO 550
      I23=IA(I21)
  500 IF(IA(I23).EQ.NB1) GO TO 600
      IF(IA(I23+1).EQ.0) GO TO 550
      I23=IA(I23+1)
      GO TO 500
C------------------- NO, CALL BOXING ROUTINE ---
  550 CALL BOXC
      GO TO 800
C------------------ IS ALL THE EDGE SCANNED ?---
  600 IF(I21.EQ.I22) GO TO 750
C------------------ YES, GET NEXT EDGE OR RETURN ---
C---------------- NO, INCREMENT BOX NUMBER ---
```

```
FORTRAN IV-PLUS V02-04G          14:42:18     29-MAR-78              PAGE 43
RBMC.FTN          /14/TR:BLOCKS/WR

            IF(I21.EQ.I2N) GO TO 300
            GO TO 200
      C------------------ INCREMENT IN Y DIRECTION ---
        650 I21=I21+IFIX(YSTEP)*IBOXES
            JBOX1=JBOX1+IFIX(YSTEP)
            GO TO 450
      C------------------ INCREMENT IN X DIRECTION ---
        700 I21=I21+IFIX(XSTEP)
            IBOX1=IBOX1+IFIX(XSTEP)
            GO TO 450
        750 XSTEP=ABS(XSTEP)
            YSTEP=ABS(YSTEP)
      C----------------- IS SCAN COMPLETE ?---
            IF(NP.EQ.NC) GO TO 800
      C------------------ NO, GET NEXT EDGE ---
            I2N=I22
            X1=A(IEND2)
            Y1=A(IEND2+1)
            IEND2=IA(IEND2+2)
            X2=A(IEND2)
            Y2=A(IEND2+1)
            GO TO 150
      C------------------ YES, RETURN ---
        800 RETURN
            END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES

$CODE1  003216   839                RW,I,CON,LCL
$IDATA  000046    19                RW,D,CON,LCL
$VARS   000154    54                RW,D,CON,LCL
$TEMPS  000004     2                RW,D,CON,LCL
.$$$$.  027340  6000                RW,D,OVR,GBL
CBLOCK  000424   138                RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 033430   7052
```

```
FORTRAN IV-PLUS V02-04G          14:43:12    29-MAR-78            PAGE 44
RBMC.FTN          /I4/TR:BLOCKS/WR

0001            SUBROUTINE LIMIT(NREQ)
          C
          C------------------ CHECK MEMORY ALLOCATION ---
          C
0002            INCLUDE 'CBLOCK.FTN'
0003 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *        .                 NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *        .                 TOEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *        .                 YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *        .                 CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *        .                 NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0004 *          LOGICAL EFLAG
          C
0005            IF((NEMPTG+NREQ).LE.M4.AND.(NEMPT+NREQ).LE.M4) RETURN
          C
0006            EFLAG=.TRUE.
0007            WRITE(6,1000)
0008            CALL FINISH
          C
0009       1000 FORMAT(39H !!! ERROR : MEMORY ALLOCATION EXCEEDED)
0010            END

PROGRAM SECTIONS

 NAME       SIZE                  ATTRIBUTES

$CODE1  000204     66             RW,I,CON,LCL
$IDATA  000054     22             RW,D,CON,LCL
CBLOCK  000424    138             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 000704    226

NO FPP INSTRUCTIONS GENERATED
```

```
FORTRAN IV-PLUS V02-04G         14:43:16    29-MAR-78           PAGE 45
RBMC.FTN          /14/TR:BLOCKS/WR

0001            SUBROUTINE FINISH
          C
          C------------------- TIDY UP AND STOP ---
          C
0002            INCLUDE 'COMMON.FTN'
0003 *          COMMON A(3000)
0004 *          DIMENSION IA(1)
0005 *          EQUIVALENCE (A,IA)
0006            INCLUDE 'CBLOCK.FTN'
0007 *          COMMON /CBLOCK/ HED(20),NBLOKM,NBOXES,M1,M2,M3,M4,
     *         .                NBLOKS,NCYC,MCYCLE,NEMPT,RHO,EFLAG,TFRAC,
     *         .                TDEL,IBOXES,JBOXES,XL,XU,YL,YU,BSIZE,SFACT,XSIZE,
     *         .                YSIZE,UDMAX,UMOST,STIFN,STIFS,FRIC,BETA,BDT,TMAX,
     *         .                CON1,CON2,ALPHA,GRAVX,GRAVY,LOC1,LOC2,NUPDAT,NB1,
     *         .                NVARB,NFRAG,NPR,NEMPTC,NEMPTD,NEMPTG,IEND1,LBLOCK
0008 *          LOGICAL EFLAG
          C
0009            CALL PLOTND
0010            WRITE(6,2000) MCYCLE,NUPDAT
          C
          C------------------- WRITE RESTART FILE IF NO ERRORS ---
0011            IF(EFLAG) GOTO 100
0012            REWIND 1
0013            WRITE(1) (HED(I),I=1,LBLOCK)
0014            WRITE(1) (A(I),I=1,M4)
0015            WRITE(6,2001)
0016        100 STOP
          C
0017       2000 FORMAT(30X,13H TOTAL CYCLES,I10/
               .       30X,13H NO. UPDATES ,I10)
0018       2001 FORMAT(30X,32H A RESTART FILE HAS BEEN WRITTEN)
          C
0019            END

PROGRAM SECTIONS

 NAME       SIZE                 ATTRIBUTES

$CODE1   000364    122           RW,I,CON,LCL
$IDATA   000120     40           RW,D,CON,LCL
$VARS    000004      2           RW,D,CON,LCL
.$$$$.   027340   6000           RW,D,OVR,GBL
CBLOCK   000424    138           RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 030474  6302

NO FPP INSTRUCTIONS GENERATED

,CUNDALL.LST/-SP=RBMC/14/LI:1/CO:10
```

APPENDIX XV: LISTING OF PROGRAM JOINT

NOTE: All arguments, common block symbols and array variables are defined on the listing itself.

```
      SUBROUTINE JOINT(DUS,DUN,STRS,STRN,JID,RIGID)
      LOGICAL RIGID
      COMMON /FRIC/ PHIB,AKS,AKN,AKD,AJRC,DEGRAD
      DIMENSION SS(50),SN(50),US(50),UN(50),UND(50),D(50)
C
C   DUS  = SHEAR DISPLACEMENT INCREMENT - INPUT TO <JOINT>
C   DUN  = NORMAL      "            "        "    "    "
C   STRS = NEW SHEAR STRESS - OUTPUT FROM <JOINT>
C   STRN =  "  NORMAL  "             "     "     "
C
C   JID = JOINT ID;  IF JID < 0 THE JOINT WILL BE INITIALIZED
C                    I.E. DAMAGE WILL BE RESET TO ZERO AND
C                    STRESSES AND DISPLACEMENTS ZEROED
C
C   IF RIGID = .TRUE. JOINT IS RIGID IN THE NORMAL DIRECTION
C      (IN THIS CASE, STRN MUST BE INPUT TO <JOINT>)
C                                   -----
C
C   PHIB = RESIDUAL (OR BASE) FRICTION ANGLE IN DEGREES
C   AKS  = ELASTIC SHEAR STIFFNESS
C   AKN  =     "    NORMAL     "
C   AKD  = DILATION CONSTANT
C   AJRC = JOINT ROUGHNESS COEFFICIENT (SEE BARTON)
C   DEGRAD CONVERSION FACTOR FROM DEGREES TO RADIANS
C
C   SS(JID) = SHEAR STRESS FOR JOINT NUMBER JID
C   SN(JID) = NORMAL  "      "     "     "     "
C   US(JID) = SHEAR DISPLACEMENT "      "     "
C   UN(JID) = NORMAL      "       "     "     "
C  UND(JID) = VIRTUAL NORMAL DISPLACEMENT DUE TO DILATION
C    D(JID) = "DAMAGE" (SEE TEXT)
C
      IF(JID.LE.0) GOTO 300
C-------------------- GET NORMAL STRESS FIRST ---
      UN(JID)=UN(JID)+DUN
      SNOLD=SN(JID)
      IF(.NOT.RIGID) GOTO 10
      SN(JID)=STRN
      GOTO 15
   10 SN(JID)=FSN(UN(JID))
      STRN=SN(JID)
   15 SNAV=0.5*(SNOLD+SN(JID))
C
C
C-------------------- NOW FOR THE SHEAR STRESS ---
C
C---ELASTIC INCREMENTS FIRST---
      SSNEW=SS(JID)+AKS*DUS
C---CHECK FOR UNLOADING---
      IF(SIGN(1.0,SNNEW).NE.SIGN(1.0,DUS)) GOTO 50
C---MUST BE LOADING---
C---CHECK IF BELOW YIELD---
      SSMAX=SNAV*TAN(PHIB*DEGRAD)
      IF(ABS(SSNEW).LE.SSMAX) GOTO 50
C---WE MUST BE IN PEAK REGION---
C---APPARENT SHEAR DISP (AS FAR AS CURVE IS CONCERNED)---
```

```
      USAPP=D(JID)/SNAV+DUS
C---MAGNITUDE OF STRENGTH---
      SSADD=FSS(USAPP,SNAV)
      SSPK=SSMAX+SSADD
C---CHECK IF WE EXCEED STRENGTH---
      IF(ABS(SSNEW).LE.SSPK) GOTO 50
C---YES, REDUCE SHEAR STRENGTH AND ACCUMULATE DAMAGE---
      SSNEW=SIGN(SSPK,SSNEW)
      IF(SSADD.EQ.0.0) GOTO 50
      D(JID)=D(JID)+SNAV*ABS(DUS)
C---COMPUTE VIRTUAL NORMAL DISPLACEMENT DUE TO DILATION---
      UND(JID)=UND(JID)+AKD*(1.0/SNAV-1.0)*DUS
C---NEW, FINAL SHEAR STRESS---
   50 SS(JID)=SSNEW
      STRS=SSNEW
      RETURN
C
C---INITIALIZATION---
C
  300 JJ=-JID
      SS(JJ)=0.0
      SN(JJ)=0.0
      US(JJ)=0.0
      UN(JJ)=0.0
      UND(JJ)=0.0
  310 D(JJ) =0.0
      RETURN
      END
```

```
      FUNCTION FSS(US,SN)
C
C    "BUMP" ON STRESS/STRAIN CURVE
C    (NORMALIZED)
C
      COMMON /FRIC/ PHIB,AKS,AKN,AKD,AJRC,DEGRAD
      DIMENSION Y(11)
      DATA Y /0.0,0.32,0.61,0.82,0.94,1.0,0.93,0.54,0.14,
     .        0.02,0.0/
      DATA NP /10/
C---SCALE DISP, SO THAT MAX DISP = NORMAL STRESS ---
      SCL=SN
C---CHECK FOR END OF CURVE--
      IF(US.GE.SCL) GOTO 100
      USSCL=US/SCL*FLOAT(NP)
      IGRF=USSCL+1.0
      IGRF=MIN0(IGRF,NP)
      YINT=Y(IGRF)+(USSCL-FLOAT(IGRF-1))*(Y(IGRF+1)-Y(IGRF))
C---SCALE STRESS ACCORDING TO BARTON'S FORMULA---
      YMAX=SN*(TAN((AJRC*ALOG10(1.0/SN)+PHIB)*DEGRAD)
     .    -TAN(PHIB*DEGRAD))
      FSS=YINT*YMAX
      RETURN
  100 FSS=0.0
      RETURN
      END
```

```
      FUNCTION FSN(UN)
      COMMON /FRIC/ PHIB,AKS,AKN
C
C   LINEAR NORMAL STRESS/DISPLACEMENT
C
      FSN=AKN*UN
      RETURN
      END
```

APPENDIX XVI : LISTING OF PROGRAM DBLOCK AND LIST OF FORTRAN NAMES

NMAX = maximum number of nodes

MMAX = maximum number of zones

IMAX = maximum number of zones about a node

IFLAG = indicator of type of input provided

KTOT = number of 4-zone cells in the generation of a regular columnar mesh

LCONT = number of initial contacts

X(N), Y(N) = coordinates of node N

XD(N), YD(N) = velocity components of node N

N = node number

M = zone number

I = index designating ordering of zones about a node

J = index designating ordering of nodes about a zone

XX(M), YY(M), XY(M) = stress components in zone M

AM(M) = mass of zone M

GPM(N) = grid point mass of node N

LAME1(M), LAME2(M) = Lamé constants in zone M

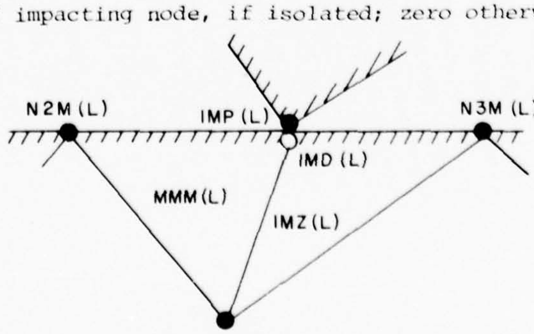
COHES(M), TANPHI(M), TANPSI(M), = plastic parameters in zone M

MAN(N,I) = I^{th} zone about node N

NAM(M,J) = J^{th} node about zone M

IMP(L), IMD(L), N2M(L), N3M(L) see adjacent figure

XNC(L) = mass of impacting node, if isolated; zero otherwise



LOCAL NAMES FOR CONTACT L

STNL = contact stiffness (loading)

STNU = contact stiffness (unloading)

DN = maximum normal displacement

STSH = shear stiffness

XMU = coefficient of friction

NITER = maximum number of iterations

FRAC = fraction of critical time step

GRAV = gravity

RMIN, FMIN = parameters for stiffness-proportional damping

ARAT = minimum aspect ratio

TFRAC = parameter for "tickling"

NPRI = number of iterations between printed outputs

NPLOT = number of iterations between points in plotted history

SCALEX, SCALEY = scales for mesh plots

ITPL(I) = iteration numbers at which mesh plots are requested

NBLOCK = number of blocks

SCALE = scale for plot of computer generated mesh

NCORN = number of corners defining the block

LIST(1,I)= I^{th} corner of block 1

AMAXL = maximum edge length desired

PROGRAM LISTING - DBLOCK

```
FORTRAN IV-PLUS V02-04G          11:24:54     29-MAR-78           PAGE 1
DBLOCK.FTN       /TR:BLOCKS/WR

0001            PROGRAM DBLOCK
          C*************************************************************
          C                                                             *
          C        DRIVING ROUTINE FOR THE PROGRAM                      *
          C                                                             *
          C*************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *        .    XNPH(70),YNPH(70),
     *        .    XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *        .    AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *        .    TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *        .    ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *        .    SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *        .    IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *        .    STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *        .    FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            CALL SETUP
0009            CALL CYCLE
0010            STOP
0011            END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1   000054     22             RW,I,CON,LCL
$IDATA   000002      1             RW,D,CON,LCL
CGRID    016374   3710             RW,D,OVR,GBL
COTHR    000110     36             RW,D,OVR,GBL
CPLOT    004570   1212             RW,D,OVR,GBL
CIMPC    001064    282             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 024436   5263

NO FPP INSTRUCTIONS GENERATED

,LIST.LST/LI:1/-SP=DBLOCK
```

```
FORTRAN IV-PLUS V02-04G          11:24:59     29-MAR-78            PAGE 1
SETUP.FTN         /TR:BLOCKS/WR

              SUBROUTINE SETUP
        C**************************************************************
        C                                                             *
        C         INPUT RECEPTION AND HANDLING                        *
        C                                                             *
        C**************************************************************
              INCLUDE 'COMMON.FTN'
              REAL LAME1,LAME2
              COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
             .   XNPH(70),YNPH(70),
             .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
             .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
             .   TANPSI(70),MAN(70,10),NAM(70,3)
              COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
             .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
             .   SCALEX,SCALEY
              COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
              COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
             .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
             .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
             .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
              AREA3(X1,Y1,X2,Y2,X3,Y3) = -0.5*((Y1+Y2)*(X2-X1)+
             .         (Y3+Y2)*(X3-X2)+(Y1+Y3)*(X1-X3))
        C-------INPUT VARIABLES ------------------------------------
              READ  1000, NMAX,MMAX,IMAX,IFLAG,KTOT,LCONT
              PRINT 2000, NMAX,MMAX,IMAX
              IF (IFLAG .EQ. 1) GO TO 12
              IF (IFLAG .EQ. 0) GO TO 18
              CALL MESH
              GO TO 7
           18 DO 19 N=1,NMAX
           19 READ  1001, X(N),Y(N),XD(N),YD(N)
              PRINT 2001, (N,X(N),Y(N),XD(N),YD(N),N=1,NMAX)
              DO 11 M=1,MMAX
           11 READ  1005, XX(M),YY(M),XY(M),RHO(M),LAME1(M),LAME2(M),
             .            COHES(M),TANPHI(M),TANPSI(M)
              PRINT 2002, (M,XX(M),YY(M),XY(M),RHO(M),LAME1(M),LAME2(M),
             .            COHES(M),TANPHI(M),TANPSI(M),M=1,MMAX)
              DO 1 N=1,NMAX
            1 READ  1003, (MAN(N,I),I=1,IMAX)
              PRINT 2003
              DO 2 N=1,NMAX
            2 PRINT 3003, N,(MAN(N,I),I=1,IMAX)
              READ  1004, ((NAM(M,J),J=1,3),M=1,MMAX)
              PRINT 2004, (M,(NAM(M,J),J=1,3),M=1,MMAX)
            7 READ  1006, (IMP(L),N2M(L),N3M(L),XNC(L),L=1,LCONT)
              PRINT 2005, LCONT,(L,IMP(L),XNC(L),N2M(L),N3M(L),L=1,LCONT)
              READ  1001, STNL,STNU,DN,STSH,XMU
              PRINT 2009, STNL,STNU,DN,STSH,XMU
              GO TO 13
           12 CALL INPUT
           13 READ  1002, NITER,FRAC,GRAV,ARAT,TFRAC,NPRI,NPLOT
              PRINT 2006, NITER,FRAC,GRAV,ARAT,TFRAC
              READ  1000, (ITPL(I),I=1,10)
              PRINT 2010, (ITPL(I),I=1,10)
              READ  1001, SCALEX,SCALEY
```

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FORTRAN IV-PLUS V02-04G          11:24:59    29-MAR-78            PAGE 2
SETUP.FTN        /TR:BLOCKS/WR

              PRINT 2011, SCALEX,SCALEY
              READ  1001, RMIN,FMIN
              PRINT 2012, RMIN,FMIN
        C-------INITIALIZATIONS -------------------------------------
              DO 3 N=1,NMAX
              XNPH(N) = X(N)
            3 YNPH(N) = Y(N)
        C
              IF (LCONT .EQ. 0) GO TO 6
              DO 4 L=1,LCONT
              GPM(IMP(L)) = XNC(L)
              DRN(L) = 0
              DRS(L) = 0
              XNC(L) = 0
              YNC(L) = 0
              FN(L)  = 0
              FS(L)  = 0
            4 DRST(L)= 0
            6 NPL  = 0
              DRNPH= 0
              DRSPH= 0
              DS   = 0
              ZERO = 0
              PI2  = 8.*ATAN(1.)
        C-------COMPUTE CRITICAL TIME STEP --------------------------
              DT   = 1.E20
              DO 20 N=1,NMAX
              DO 15 I=1,IMAX
              M    = MAN (N,I)
              IF (M .EQ. 0) GO TO 20
              NN   = NAM(M,2)
              IF (NAM(M,1) .EQ. N) NN=NAM(M,3)
              IF (NAM(M,2) .EQ. N) NN=NAM(M,1)
              DS   = (X(N)-X(NN))**2+(Y(N)-Y(NN))**2
              MM   = MAN(N,I+1)
              IF (MM .EQ. 0) MM=MAN(N,1)
              VMS  = (LAME1(M)+2.*LAME2(M))/RHO(M)
              VMMS = (LAME1(MM)+2.*LAME2(MM))/RHO(MM)
              DTN  = SQRT(DS/AMAX1(VMS,VMMS))
              DT   = AMIN1(DT,DTN)
           15 CONTINUE
           20 CONTINUE
              FRED = 2.*ARAT
              DT   = DT*AMIN1(FRED,1.)*FRAC
              PRINT 2008,DT
        C-------COMPUTE ZONE MASSES ---------------------------------
              DO 40 M=1,MMAX
           40 AM(M)  = RHO(M)*AREA3(X(NAM(M,1)),Y(NAM(M,1)),X(NAM(M,2)),
             .          Y(NAM(M,2)),X(NAM(M,3)),Y(NAM(M,3)))
        C-------COMPUTE GRID-POINT MASSES ---------------------------
              DO 10 N=1,NMAX
              GPMP   = 0
              DO  5 I=1,IMAX
              M      = MAN(N,I)
              IF (M .EQ. 0) GO TO 10
            5 GPMP   = GPMP+AM(M)
```

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FORTRAN IV-PLUS V02-04G          11:24:59    29-MAR-78            PAGE 3
SETUP.FTN        /TR:BLOCKS/WR

0089        10 GPM(N) = GPMP/3.
0090           PRINT 2007,(N,GPM(N),N=1,NMAX)
         C-------RAYLEIGH DAMPING -------------------------------------
0091           ALPHA  = PI2*RMIN*FMIN*DT/2.
0092           CON1   = 1.-ALPHA
0093           CON2   = 1./(1.+ALPHA)
0094           BETA   = RMIN/(PI2*FMIN)
0095           BDT    = BETA/DT
0096           BDT1   = 1.+BDT
         C-------CREATION OF NEW GRID POINTS UPON CONTACT ------------
0097           IF (IFLAG .EQ. 1) RETURN
0098           DO 50 L=1,LCONT
0099           IFL(L) = 0
0100           IFG(L) = 1
0101           CALL CREATE(L)
0102        50 CONTINUE
0103           RETURN
         C
0104      1000 FORMAT (8I10)
0105      1001 FORMAT (8F10.0)
0106      1002 FORMAT (I10,4F10.0,2I10)
0107      1003 FORMAT (10I5)
0108      1004 FORMAT (3I5)
0109      1005 FORMAT (9F8.0)
0110      1006 FORMAT (3I10,F10.0)
0111      2000 FORMAT ('0MAX NUMBER OF NODES                 ='I6,/
              .        ' MAX NUMBER OF ZONES                 ='I6,/
              .        ' MAX NUMBER OF ZONES ABOUT A NODE  ='I6)
0112      2001 FORMAT (//' NODE DATA'//5X,'N',6X,'X',11X,'Y',10X,'XD',
              .        10X,'YD',/(1X,I5,1P4E12.4))
0113      2002 FORMAT (//' ZONE DATA'//5X,'M',5X,'XX',10X,'YY',10X,'XY',
              .        10X,'AM',9X,'LAME1'7X,'LAME2'7X,'COHES'7X,'TANPHI'
              .        6X,'TANPSI'/(I6,1P9E12.4))
0114      2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
              .        5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
              .        5X,'9',5X,'10')
0115      3003 FORMAT (1X,11I6)
0116      2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
              .        5X,'2',5X,'3',/(4I6))
0117      2005 FORMAT (//' CONTACTS ESTABLISHED:'I3
              .        //' CONTACT   IMPACTING      IMPACTING'11X,'BETWEEN'
              .         /'  NUMBER      NODE             MASS'11X,'NODE AND NODE'
              .         /(3X,I3,7X,I3,7X,1PE12.4,7X,I3,6X,I3))
0118      2006 FORMAT (//' NUMBER OF ITERATIONS                ='I5,
              .         /' FRACTION OF CRITICAL TIME STEP  ='1PE12.4,
              .         /' ACCELERATION OF GRAVITY           ='1PE12.4,
              .         /' MINIMUM ASPECT RATIO OF ZONES   ='1PE12.4,
              .         /' TOLERANCE / ZONE LENGTH           ='1PE12.4)
0119      2007 FORMAT (//' GRID POINT MASSES'//5X,'N'4X,'MASS'
              .         /(I6,1PE12.4))
0120      2008 FORMAT (//' TIME INCREMENT ='1PE12.4)
0121      2009 FORMAT(//' CONTACT PROPERTIES'
              .        //' LOADING NORMAL STIFFNESS          ='1PE12.4,
              .         /' UNLOADING NORMAL STIFFNESS        ='1PE12.4,
              .         /' MAX RELATIVE NORMAL DISPLACEMENT='1PE12.4,
              .         /' SHEAR STIFFNESS                   ='1PE12.4,
```

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FORTRAN IV-PLUS V02-04G          11:24:59    29-MAR-78            PAGE 4
SETUP.FTN        /TR:BLOCKS/WR

                .          /' COEFFICIENT OF FRICTION          ='1PE12.4)
0122      2010 FORMAT (//' MESH PLOTTED AT ITERATIONS       ='(1515))
0123      2011 FORMAT (//' SCALE FOR PLOTTING: X-DIRECTION ='1PE12.4,
                .          /'                     Y-DIRECTION ='1PE12.4)
0124      2012 FORMAT (//' RAYLEIGH DAMPING PARAMETERS'
                .          /'          PERCENT DAMPING         ='2PF12.4,
                .          /'          AT FREQUENCY (HZ)       ='1PE12.4)
0125      2100 FORMAT (//' NO SPACE TO STORE NEW LINK -- JOB ABORTED')
0126           END

PROGRAM SECTIONS

 NAME        SIZE                      ATTRIBUTES

$CODE1   005266   1371                 RW,I,CON,LCL
$PDATA   000010      4                 RW,D,CON,LCL
$IDATA   002634    718                 RW,D,CON,LCL
$VARS    000106     35                 RW,D,CON,LCL
$TEMPS   000010      4                 RW,D,CON,LCL
CGRID    016374   3710                 RW,D,OVR,GBL
COTHR    000110     36                 RW,D,OVR,GBL
CPLOT    004570   1212                 RW,D,OVR,GBL
CIMPC    001064    282                 RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 034630  7372

,LIST.LST/LI:1/-SP=SETUP
```

```
FORTRAN IV-PLUS V02-04G          11:25:45     29-MAR-78            PAGE 1
CYCLE.FTN        /TR:BLOCKS/WR

0001            SUBROUTINE CYCLE
          C****************************************************************
          C                                                               *
          C        DRIVING ROUTINE FOR THE COMPUTATION CYCLE              *
          C                                                               *
          C****************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .   XNPH(70),YNPH(70),
     *         .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *         .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            CALL PLOTST(0.025,'CM')
0009            DO 100 ITER=1,NITER
0010            CALL OUTPUT
0011            CALL MOTION
0012            CALL STRESS
0013            TIME = TIME+DT
0014        100 CONTINUE
0015            CALL OUTPUT
0016            WRITE (2) BUF1
0017            WRITE (2) BUF2
0018            WRITE (4) BUF3
0019            WRITE (4) BUF2
0020            CALL PLOT(0.,0.,3)
0021            CALL PLOTND
0022            RETURN
0023            END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1   000310    100             RW,I,CON,LCL
$PDATA   000020      8             RW,D,CON,LCL
$IDATA   000050     20             RW,D,CON,LCL
$TEMPS   000002      1             RW,D,CON,LCL
CGRID    016374   3710             RW,D,OVR,GBL
COTHR    000110     36             RW,D,OVR,GBL
CPLOT    004570   1212             RW,D,OVR,GBL
CIMPC    001064    282             RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 024762  5369

,LIST.LST/LI:1/-SP=CYCLE
```

```
FORTRAN IV-PLUS V02-04G          11:25:52    29-MAR-78           PAGE 1
MOTION.FTN       /TR:BLOCKS/WR

              SUBROUTINE MOTION
        C***********************************************************
        C                                                          *
        C        MOMENTUM BALANCE IN CONTINUA                      *
        C                                                          *
        C***********************************************************
              INCLUDE 'COMMON.FTN'
              REAL LAME1,LAME2
              COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
             .   XNPH(70),YNPH(70),
             .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
             .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
             .   TANPSI(70),MAN(70,10),NAM(70,3)
              COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
             .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
             .   SCALEX,SCALEY
              COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
              COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
             .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
             .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
             .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
        C.......................................
              COMMON /SHEAR/ FXSUM,FYSUM
              FXSUM = 0
              FYSUM = 0
        C.......................................
        C-------MAIN ITERATION LOOP ---------------------
              DO 100 N=1,NMAX
              IF (GPM(N) .LE. 0) GO TO 100
              FX    = 0
              FY    = 0
              DO 90 I=1,IMAX
              M     = MAN(N,I)
              IF (M .EQ. 0) GO TO 90
              IF (N .NE. NAM(M,1)) GO TO 10
              DX    = X(NAM(M,3))-X(NAM(M,2))
              DY    = Y(NAM(M,3))-Y(NAM(M,2))
              GO TO 30
           10 IF (N .NE. NAM(M,2)) GO TO 20
              DX    = X(NAM(M,1))-X(NAM(M,3))
              DY    = Y(NAM(M,1))-Y(NAM(M,3))
              GO TO 30
           20 DX    = X(NAM(M,2))-X(NAM(M,1))
              DY    = Y(NAM(M,2))-Y(NAM(M,1))
           30 FX    = FX+XX(M)*DY-XY(M)*DX
              FY    = FY+XY(M)*DY-YY(M)*DX
           90 CONTINUE
           95 FX    = FX/2.
              FY    = FY/2.
        C.......................................
              IF (N.LT.25 .OR. N.GT.29) GO TO 96
              FXSUM = FXSUM+FX
              FYSUM = FYSUM+FY
           96 CONTINUE
        C.......................................
              ACCX = FX/GPM(N)
```

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FORTRAN IV-PLUS V02-04G          11:25:52     29-MAR-78            PAGE 2
MOTION.FTN        /TR:BLOCKS/WR

              ACCY = FY/GPM(N)-GRAV
              XD(N)= XD(N)+ACCX*DT
              YD(N)= YD(N)+ACCY*DT
          100 CONTINUE
        C--------CONTACT AND BOUNDARY CONDITIONS --------------------
              IF (IFLAG .NE. 1) CALL INTRAC
              CALL BOUNDY
              IF (IFLAG .NE. 1) CALL INTRA1
              CALL BOUNDY
        C--------NEW COORDINATES ---------------------------
              DO 110 N=1,NMAX
              XN    = X(N)+XD(N)*DT
              YN    = Y(N)+YD(N)*DT
              XNPH(N) = 0.5*(X(N)+XN)
              YNPH(N) = 0.5*(Y(N)+YN)
              X(N) = XN
              Y(N) = YN
          110 CONTINUE
              RETURN
              END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES

$CODE1   001250    340              RW,I,CON,LCL
$IDATA   000002      1              RW,D,CON,LCL
$VARS    000046     19              RW,D,CON,LCL
$TEMPS   000004      2              RW,D,CON,LCL
CGRID    016374   3710              RW,D,OVR,GBL
COTHR    000110     36              RW,D,OVR,GBL
CPLOT    004570   1212              RW,D,OVR,GBL
CIMPC    001064    282              RW,D,OVR,GBL
SHEAR    000010      4              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 025714   5606

,LIST.LST/LI:1/-SP=MOTION
```

```
FORTRAN IV-PLUS V02-04G          11:26:06    29-MAR-78           PAGE 1
BOUNDY.FTN        /TR:BLOCKS/WR

0001            SUBROUTINE BOUNDY
          C***************************************************************
          C                                                              *
          C        BOUNDARY CONDITIONS                                   *
          C                                                              *
          C***************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .   XNPH(70),YNPH(70),
     *         .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *         .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
          C-------BOTTOM BOUNDARY FIXED ----------------------------
0008            XD(3) = 0
0009            YD(1) = 0
0010            YD(2) = 0
0011            YD(3) = 0
0012            YD(4) = 0
0013            YD(5) = 0
          C-------TOP BOUNDARY RATHER PECULIAR, I'D SAY ------------
0014            FREDA = 0
0015            FREDB = 0
0016            IF (ITER .LT. 100) FREDB=-0.1
0017            IF (ITER .GT. 1000) FREDA=-0.1
0018            DO 10 N=25,29
0019            XD(N) = FREDA
0020         10 YD(N) = FREDB
0021            RETURN
0022            END

PROGRAM SECTIONS

 NAME        SIZE                  ATTRIBUTES

$CODE1  000166     59              RW,I,CON,LCL
$PDATA  000004      2              RW,D,CON,LCL
$VARS   000012      5              RW,D,CON,LCL
CGRID   016374   3710              RW,D,OVR,GBL
COTHR   000110     36              RW,D,OVR,GBL
CPLOT   004570   1212              RW,D,OVR,GBL
CIMPC   001064    282              RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 024564  5306

,LIST.LST/LI:1/-SP=BOUNDY
```

```
FORTRAN IV-PLUS V02-04G         11:26:12    29-MAR-78          PAGE 1
INTRAC.FTN       /TR:BLOCKS/WR

            SUBROUTINE INTRAC
            INCLUDE 'COMMON.FTN'
            REAL LAME1,LAME2
            COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     .        XNPH(70),YNPH(70),
     .        XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     .        AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     .        TANPSI(70),MAN(70,10),NAM(70,3)
            COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     .        ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     .        SCALEX,SCALEY
            COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
            COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     .        IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     .        STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,IFRAC,
     .        FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
            COMMON /INTRA/ FLAG(10)
            AREA3(X1,Y1,X2,Y2,X3,Y3) = -0.50*((Y1+Y2)*(X2-X1)+
     .               (Y3+Y2)*(X3-X2)+(Y1+Y3)*(X1-X3))
      C-------VELOCITY CORRECTION DUE TO CONTACT FORCES ----------
      C-----------------------------------------------------------
            DO 50 L=1,LCONT
            IF (IFG(L) .NE. 1) GO TO 50
            IF (IFR(L) .NE. 0) GO TO 50
            N1     = IMP(L)
            NW     = IMD(L)
            N2     = N2M(L)
            N3     = N3M(L)
      C
            IF (IFL(L) .EQ. 0) GO TO 30
            IF (DRST(L)) 20,30,10
         10 N2     = NW
            GO TO 30
         20 N3     = NW
      C
         30 XND    = YNPH(N2)-YNPH(N3)
            YND    = XNPH(N3)-XNPH(N2)
            FRED   = SQRT(XND*XND+YND*YND)
            XND    = XND/FRED
            YND    = YND/FRED
      C
            C11    = YND*YNC(L)+XND*XNC(L)
            C12    = YND*XNC(L)-XND*YNC(L)
            FNP    = C11*FN(L)+C12*FS(L)
            FSP    =-C12*FN(L)+C11*FS(L)
      C
            BDT2   = BDT1
      C     IF (ABS(FSP) .GE. 0.98*XMU*ABS(FNP)) BDT2=1.
            FNP    = FNP*BDT1
            FSP    = FSP*BDT2
            XD(N1)= XD(N1)+(FNP*XND-FSP*YND)*DT/GPM(N1)
            YD(N1)= YD(N1)+(FNP*YND+FSP*XND)*DT/GPM(N1)
            XD(NW)= XD(NW)-(FNP*XND-FSP*YND)*DT/GPM(NW)
            YD(NW)= YD(NW)-(FNP*YND+FSP*XND)*DT/GPM(NW)
            XNC(L)= XND
            YNC(L)= YND
```

```
FORTRAN IV-PLUS V02-04G          11:26:12    29-MAR-78           PAGE 2
INTRAC.FTN       /TR:BLOCKS/WR

0040          FN(L) = FNP/BDT1
0041          FS(L) = FSP/BDT2
0042       50 CONTINUE
0043          RETURN
0044          END

PROGRAM SECTIONS

 NAME        SIZE                    ATTRIBUTES

$CODE1  001054   278                 RW,I,CON,LCL
$VARS   000052    21                 RW,D,CON,LCL
$TEMPS  000002     1                 RW,D,CON,LCL
CGRID   016374  3710                 RW,D,OVR,GBL
COTHR   000110    36                 RW,D,OVR,GBL
CPLOT   004570  1212                 RW,D,OVR,GBL
CIMPC   001064   282                 RW,D,OVR,GBL
INTRA   000050    20                 RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 025560  5560

,LIST.LST/LI:1/-SP=INTRAC
```

```
FORTRAN IV-PLUS V02-04G          11:26:23    29-MAR-78           PAGE 1
INTRA1.FTN      /TR:BLOCKS/WR

0001            SUBROUTINE INTRA1
        C***********************************************************
        C                                                          *
        C        REZONING CAPABILITIES                             *
        C                                                          *
        C***********************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *        .   XNPH(70),YNPH(70),
     *        .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *        .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *        .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *        .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *        .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *        .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *        .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *        .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            COMMON /INTRA/ FLAG(10)
0009            COMMON/CI1/N1,NW,GPM1,GPMW,XND,YND,VNN1,VNNW,VRN,VRS,DRNPH,DRSPH,L
0010            AREA3(X1,Y1,X2,Y2,X3,Y3) = -0.5*((Y1+Y2)*(X2-X1)+
              .       (Y3+Y2)*(X3-X2)+(Y1+Y3)*(X1-X3))
        C-------COMPUTE FORCES FROM DISPLACEMENTS ------------------
        C----------------------------------------------------------
0011            DO 500 L=1,LCONT
0012            IF (IFG(L) .NE. 1) GO TO 500
0013            N1     = IMP(L)
0014            NW     = IMD(L)
0015            GPM1   = GPM(N1)
0016            GPMW   = GPM(NW)
        C-------RELATIVE MOVEMENTS --------------------------------
0017            XND    = XNC(L)
0018            YND    = YNC(L)
0019            VNN1   = XD(N1)*XND+YD(N1)*YND
0020            VNNW   = XD(NW)*XND+YD(NW)*YND
0021            VRN    = VNNW-VNN1
0022            VSN1   =-XD(N1)*YND+YD(N1)*XND
0023            VSNW   =-XD(NW)*YND+YD(NW)*XND
0024            VRS    = VSNW-VSN1
0025            DRNN   = DRN(L)+VRN*DT
0026            DRNPH  = 0.5*(DRN(L)+DRNN)
0027            DRN(L) = DRNN
0028            DRSS   = DRS(L)+VRS*DT
0029            DRSPH  = 0.5*(DRS(L)+DRSS)
0030            DRS(L) = DRSS
0031            DRST(L)= DRST(L)+VRS*DT
        C-------BROKEN CONTACT ------------------------------------
0032            IF (DRNPH .GE. -0.1) GO TO 10
        CCCCC PRINT 4000,L,ITER
0033     4000 FORMAT(' BRE'I3,I5)
0034            RTOLC  = TOLC(L)-DRST(L)
        CCCCC PRINT 2728,TOLC(L),DRST(L),RTOLC
0035     2728 FORMAT(' TOLC,DRST,RTOLC'1P3E12.4)
```

```
      IFG(L) = 0
      FN(L)  = 0
      FS(L)  = 0
      DRN(L) = 0
      DRS(L) = 0
      DRST(L)= 0
C-------FOR REDUNDANT CONTACTS -------------
      DO 5 LC=1,LCONT
      IF (IFG(LC) .EQ.  0) GO TO 5
      IF (IMP(LC) .NE. NW) GO TO 5
      IFR(LC) = 0
      GO TO 500
    5 CONTINUE
C
      IF (IFL(L) .EQ. 1) GO TO 215
      GO TO 500
C-------CALL APPROPRIATE INTERACTION ROUTINE ---------------
   10 IF (IFR(L) .EQ. 1) GO TO 95
      CALL POINT
C
C-------TICKLE REZONING --------------------------------------
C-------IS IT NEEDED -----------------------
   50 IF (ABS(DRST(L)) .LT. TOL) GO TO 500
      IF (IFL(L) .NE. 0) GO TO 95
C-------DO IT ------------------------------
CCCCC PRINT 999,L,ITER,DRST(1),DRST(2),TOLC(1),TOLC(2)
  999 FORMAT (' TIC'I3,I5,1P4E12.4)
      N2     = N2M(L)
      N3     = N3M(L)
      N4     = N4M(L)
      MW     = IMZ(L)
      MM     = MMM(L)
      DRST(L)= 0
C
      AREAP  = AREA3(X(N1),Y(N1),X(NW),Y(NW),X(N4),Y(N4))
      IF (AREAP .GT. 0) GO TO 53
      NN     = N2
      M2     = MM
      M3     = MW
      FLAG(L)= 1.
      GO TO 55
   53 NN     = N3
      M2     = MW
      M3     = MM
      FLAG(L)=-1.
C
   55 AREA   = ABS(AREA3(X(NN),Y(NN),X(NW),Y(NW),X(N4),Y(N4)))
      TMASS  = AM(M2)*AREAP/AREA
      TMAS3  = TMASS/3.
      GPM(N2)= GPM(N2)+TMAS3
      GPM(N3)= GPM(N3)-TMAS3
      AM(MM) = AM(MM)+TMASS
      AM(MW) = AM(MW)-TMASS
C
      X(NW)  = X(N1)-DRN(L)*XND-DRS(L)*YND
      Y(NW)  = Y(N1)-DRN(L)*YND+DRS(L)*XND
```

```
          XD(NW) = XD(NW)+TMAS3*(XD(N3)-XD(N2))/GPMW
          YD(NW) = YD(NW)+TMAS3*(YD(N3)-YD(N2))/GPMW
C
          XND    = YNPH(NN)-YNPH(N4)
          YND    = XNPH(N4)-XNPH(NN)
          FRED   = XND*XND+YND*YND
C
C         GO TO 56
          DX = X(N3)-X(N2)
          DY = Y(N3)-Y(N2)
          DA = X(NW)-X(N2)
          DB = Y(NW)-Y(N2)
          FR = 0.05*(DX*DX+DY*DY)
          IF (DB*DX-DA*DY .LT. FR) GO TO 56
CCCCC PRINT 4000,L,ITER
          IFG(L) = 0
          FN(L)  = 0
          FS(L)  = 0
          DRN(L) = 0
          DRS(L) = 0
          DRST(L)= 0
          GO TO 500
      56 CONTINUE
C-------DELETION OF TRIANGLES ------------------------------
C-------IS IT NEEDED -----------------------
          IF (2.*AREA/FRED .GE. ARAT) GO TO 500
C-------DO IT ------------------------------
CCCCC PRINT 1001, L,ITER,DRST(L),TOLC(L)
    1001 FORMAT(' DEL'I3,I5,1P2E12.4)
C-------LOCATE SIDE ZONE AND NODE
          NWT    = NW
          MS     = M2
C-------LOCATE NODE
      64 DO 61 I=1,3
          N6T    = NAM(MS,I)
          IF (N6T .NE. NN .AND. N6T .NE. NWT) GO TO 62
      61 CONTINUE
      62 N6      = N6T
C-------LOCATE ZONE
          DO 631 I=1,IMAX
          MST    = MAN(NN,I)
          IF (MST .EQ. MS .OR. MST .EQ. 0) GO TO 631
          DO 63 J=1,IMAX
          IF (MST .NE. MAN(N6,J)) GO TO 63
          MS     = MST
          NWT    = N6
          GO TO 64
      63 CONTINUE
     631 CONTINUE
          IF (MS .EQ. M2) MS=M3
C-------ADJUST VELOCITIES
          DENOM  = GPMW+GPM(NN)-TMAS3
          NO     = N2+N3-NN
          XD(NN) = (GPMW*XD(NW)+GPM(NN)*XD(NN)-TMAS3*XD(NO))/DENOM
          YD(NN) = (GPMW*YD(NW)+GPM(NN)*YD(NN)-TMAS3*YD(NO))/DENOM
          DRST(L)= SQRT((X(NW)-X(N2))**2+(Y(NW)-Y(N2))**2)*FLAG(L)
```

```
          TOLC(L)= 1.5*ABS(DRST(L))
C-------ADJUST MASSES
          TMAS3  = AM(M2)/3.
          GPM(NN)= GPM(NN)+GPMW-TMAS3
          GPM(NO)= GPM(NO)+TMAS3
          GPM(NW)= 0
          AM(M3) = AM(M3)+AM(M2)
          AM(M2) = 0
C-----ADJUST LINKS
          IF (FLAG(L) .GT. 0) N2M(L)=N6
          IF (FLAG(L) .LT. 0) N3M(L)=N6
          DO 69 I=1,LCONT
          IF (N2M(I) .EQ. NW) N2M(I)=N2
          IF (N3M(I) .EQ. NW) N3M(I)=N3
       69 CONTINUE
C
          DO 70 I=1,IMAX
          IF (MAN(NN,I) .NE. M2) GO TO 70
          MAN(NN,I) = M3
          GO TO 72
       70 CONTINUE
C
       72 DO 75 I=1,IMAX
          IF (MAN(N4,I) .NE. M2) GO TO 75
          MAN(N4,I) = 0
          GO TO 80
       75 CONTINUE
C
       80 DO 90 I=1,3
          IF (NAM(MW,I) .NE. NW) GO TO 90
          NAM(MW,I) = NN
          GO TO 92
       90 CONTINUE
C
       92 IMD(L) = NN
          IFL(L) = 1
          IF (FLAG(L) .GT. 0) MMM(L)=MS
          IF (FLAG(L) .LT. 0) IMZ(L)=MS
C-------REDUNDANT CONTACTS
          DO 57 LC=1,LCONT
          IF (IFG(LC) .EQ.  0) GO TO 57
          IF (IMP(LC) .NE. NN) GO TO 57
          IF (IMD(LC) .NE. N1) GO TO 57
          IF (IFR(LC) .EQ.  1) GO TO 57
          IFR(L) = 1
CCCCC PRINT 1002, L,ITER
     1002 FORMAT (' RED'I3,I5)
          GO TO 58
       57 CONTINUE
C
       58 CONTINUE
CCCCC PRINT 2003
          DO 93 N=1,NMAX
CCCCC PRINT 3003, N,(MAN(N,I),I=1,IMAX)
       93 CONTINUE
CCCCC PRINT 2004, (M,(NAM(M,J),J=1,3),AM(M),M=1,MMAX)
```

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FORTRAN IV-PLUS V02-04G         11:26:23    29-MAR-78            PAGE 5
INTRA1.FTN       /TR:BLOCKS/WR

              CCCCC PRINT 2222, (K,IFG(K),IFL(K),IFR(K),IMP(K),IMD(K),N2M(K),N3M(K),
              CCCCC.            MMM(K),IMZ(K),K=1,LCONT)
0169           2222 FORMAT (//' CONTACT LINKS'
                    .         /'    L   IFG  IFL  IFR  IMP  IMD  N2M  N3M  MMM  IMZ'
                    .         /(1X,10I5))
0170           2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
                    .         5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
                    .         5X,'9',5X,'10')
0171           3003 FORMAT (1X,11I6)
0172           2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
                    .         5X,'2',5X,'3',5X,'MASS'/(4I6,1PE12.4))
0173                GO TO 500
              C-------RE-CREATION OF A DELETED NODE ----------------------
              C-------IS IT NEEDED -----------------------
0174             95 IF (ABS(DRST(L)) .LE. TOLC(L)) GO TO 500
              C-------DO IT -----------------------------
              CCCCC PRINT 1000, L
0175           1000 FORMAT(' CRE'I3)
0176                IFR(L) = 0
0177                IF (DRST(L) .GT. 0) N2M(L)=NW
0178                IF (DRST(L) .LT. 0) N3M(L)=NW
0179                IF (IMZ(L).EQ.0 .OR. MMM(L).EQ.0) INOT=1
              C
0180                IF (IMZ(L) .NE. MMM(L)) GO TO 197
0181                IFG(L) = 0
0182                GO TO 198
              C
0183            197 CALL CREATE(L)
0184            198 IF (INOT .EQ. 0) GO TO 199
0185                INOT = 0
0186                GO TO 500
              C-------MAKE REVERSE CONTACT NON-REDUNDANT
0187            199 DO 210 LC=1,LCONT
0188                IF (IFG(LC) .NE.  1) GO TO 210
0189                IF (IMP(LC) .NE. NW) GO TO 210
0190                IFR(LC) = 0
0191                GO TO 500
0192            210 CONTINUE
              C-------CREATE REVERSE CONTACT -------------
              C-------FIND CONTACT
0193            215 DO 220 LC=1,LCONT
0194                IF (IFG(LC) .EQ. 1) GO TO 220
0195                LL = LC
0196                GO TO 230
0197            220 CONTINUE
0198                LCONT = LCONT+1
0199                LL = LCONT
              C-------FIND A ZONE
0200            230 DO 240 I=1,IMAX
0201                IF (MAN(N1,I) .EQ. 0) GO TO 240
0202                MT = MAN(N1,I)
0203                GO TO 250
0204            240 CONTINUE
              C-------FIND SECOND NODE
0205            250 DO 260 J=1,3
0206                IF (NAM(MT,J) .EQ. N1) GO TO 270
```

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FORTRAN IV-PLUS V02-04G         11:26:23    29-MAR-78              PAGE 6
INTRA1.FTN       /TR:BLOCKS/WR

      260 CONTINUE
      270 J  = J+IFIX(FLAG(L))
          IF (J .EQ. 0) J=3
          IF (J .EQ. 4) J=1
          NT = NAM(MT,J)
C-------ITERATE TO BOUNDARY
      272 DO 280 I=1,IMAX
          M  = MAN(N1,I)
          IF (M .EQ. 0 .OR. M .EQ. MT) GO TO 280
          DO 275 J=1,IMAX
          IF (M .EQ. MAN(NT,J)) GO TO 290
      275 CONTINUE
      280 CONTINUE
          GO TO 310
C
      290 MT = M
          DO 300 I= 1,3
          N  = NAM(MT,I)
          IF (N .EQ. N1 .OR. N .EQ. NT) GO TO 300
          NT = N
          GO TO 272
      300 CONTINUE
C-------CREATE NEW CONTACT
      310 IMP(LC) = NW
C...CHECK......
          N2M(LC) = NT
          N3M(LC) = N1
C..............
          IFL(LC) = 0
          IFG(LC) = 1
          IFR(LC) = 0
C
          IF (RTOLC .EQ. 0) GO TO 320
          IMD(LC) = N1
          MMM(LC) = MT
          IMZ(LC) = 0
          IFL(LC) = 1
          TOLC(LC)= RTOLC
          RTOLC   = 0
          FLAG(LC)= FLAG(L)
          DRST(LC)= 0
          XND     = YNPH(N2M(LC))-YNPH(N3M(LC))
          YND     = XNPH(N3M(LC))-XNPH(N2M(LC))
          FRED    = SQRT(XND*XND+YND*YND)
          XNC(LC) = XND/FRED
          YNC(LC) = YND/FRED
          GO TO 500
C
      320 CALL CREATE(LC)
C
      500 CONTINUE
          RETURN
          END

PROGRAM SECTIONS
```

AD-A061 658 DAMES AND MOORE LOS ANGELES CA F/G 8/7
COMPUTER MODELING OF JOINTED ROCK MASSES.(U)
AUG 78 T MAINI, P CUNDALL, J MARTI DACA39-77-C-0004

UNCLASSIFIED WES-TR-N-78-4 NL

5 OF 6
AD
A061 658

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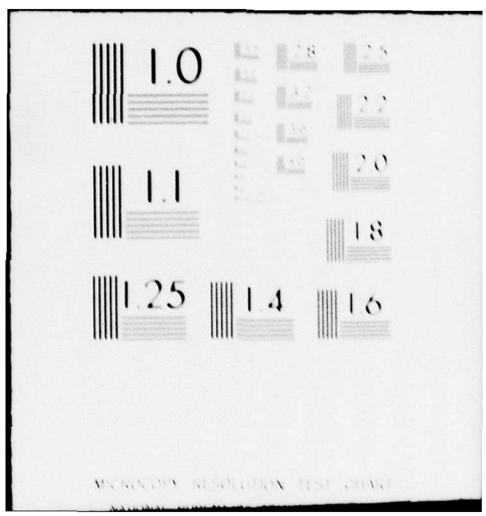
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1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART

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FORTRAN IV-PLUS V02-04G        11:27:34    29-MAR-78            PAGE 1
POINT.FTN       /TR:BLOCKS/WR

0001            SUBROUTINE POINT
          C***********************************************************
          C                                                          *
          C        CONSTITUTIVE RELATIONS FOR CORNER-EDGE CONTACTS   *
          C                                                          *
          C***********************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .   XNPH(70),YNPH(70),
     *         .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *         .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            COMMON/CI1/N1,NW,GPM1,GPMW,XND,YND,VNN1,VNNW,VRN,VRS,DRNPH,DRSPH,L
          C
          C-------NORMAL COMPONENT -----------------------------------
          C-------RIGID CONTACT ----------------------
0009            IF (DRNPH .LE. DN) GO TO 20
0010            DVNN1  = (VNNW-VNN1-2.*(DN-DRN(L))/DT)*GPMW/(GPM1+GPMW)
0011            DVNNW  = DVNN1*GPM1/GPMW
0012            FN(L)  = DN*STNL+GPM1*DVNN1/DT
0013            XD(N1) = XD(N1)+DVNN1*XND
0014            YD(N1) = YD(N1)+DVNN1*YND
0015            XD(NW) = XD(NW)+DVNNW*XND
0016            YD(NW) = YD(NW)+DVNNW*YND
0017            DRN(L) = DN
0018            DRNPH  = DN
0019            GO TO 30
          C-------FLEXIBLE CONTACT ------------------
0020         20 FN(L)  = AMIN1(FN(L)+VRN*DT*STNU,DRNPH*STNL)
0021            FN(L)  = AMAX1(FN(L),ZERO)
          C
          C-------SHEAR COMPONENT ------------------------------------
0022         30 DSST   = FN(L)*XMU
0023            DS     = DSST/STSH
          C-------NO SLIDING -------------------------
0024            IF (ABS(DRSPH) .GT. DS) GO TO 40
0025            FS(L)  = STSH*DRSPH
0026            RETURN
          C-------SLIDING ----------------------------
0027         40 DRS(L) = SIGN(DS,DRS(L))
0028            DRSPH  = DRS(L)
0029            FS(L)  = SIGN(DSST,DRS(L))
          C
0030            RETURN
0031            END
```

```
FORTRAN IV-PLUS V02-04G          11:27:45    29-MAR-78          PAGE 1
CREATE.FTN       /TR:BLOCKS/WR

0001             SUBROUTINE CREATE(L)
           C***************************************************************
           C                                                               *
           C       CREATION OF A NEW GRID POINT UPON CONTACT              *
           C                                                               *
           C***************************************************************
0002             INCLUDE 'COMMON.FTN'
0003 *           REAL LAME1,LAME2
0004 *           COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *          .   XNPH(70),YNPH(70),
     *          .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *          .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *          .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *           COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *          .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *          .   SCALEX,SCALEY
0006 *           COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *           COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *          .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *          .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *          .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
           C-------NEW NODE AND ZONE ------------------------------
0008             DO 10 N=1,NMAX
0009             IF (GPM(N) .NE. 0) GO TO 10
0010             IMD(L)= N
0011             GO TO 20
0012          10 CONTINUE
0013             NMAX  = NMAX+1
0014             IMD(L)= NMAX
0015          20 NW    = IMD(L)
           C
0016             DO 30 M=1,MMAX
0017             IF (AM(M) .NE. 0) GO TO 30
0018             IMZ(L)= M
0019             GO TO 40
0020          30 CONTINUE
0021             MMAX  = MMAX+1
0022             IMZ(L)= MMAX
0023          40 MW    = IMZ(L)
           C-------COORDINATES AND VELOCITIES ---------------------
0024             N1    = IMP(L)
0025             N2    = N2M(L)
0026             N3    = N3M(L)
0027             X(NW) = X(N1)-DRN(L)*XNC(L)-DRS(L)*YNC(L)
0028             Y(NW) = Y(N1)-DRN(L)*YNC(L)+DRS(L)*XNC(L)
0029             XNPH(NW) = X(N1)
0030             YNPH(NW) = Y(N1)
0031             D1    = SQRT((X(N2)-X(NW))**2+(Y(N2)-Y(NW))**2)
0032             D2    = SQRT((X(N3)-X(NW))**2+(Y(N3)-Y(NW))**2)
0033             FRED  = D1/(D1+D2)
0034             BILL  = 1.-FRED
0035             XD(NW)= FRED*XD(N2)+BILL*XD(N3)
0036             YD(NW)= FRED*YD(N2)+BILL*YD(N3)
0037             DRST(L) = 0
           C-------DETERMINATION OF ZONE IMPACTED -----------------
0038             DO 42 I=1,IMAX
```

```
FORTRAN IV-PLUS V02-04G          11:27:45    29-MAR-78              PAGE 2
CREATE.FTN       /TR:BLOCKS/WR

      NIN    = MAN(N2,I)
      IF (NIN .EQ. 0) GO TO 42
      DO 42 J=1,IMAX
      IF (NIN .NE. MAN(N3,J)) GO TO 42
      MM     = NIN
      MMM(L) = NIN
      GO TO 43
   42 CONTINUE
C-------REASSIGNMENT OF MASS AND OTHER PROPERTIES -------
   43 TOL    = TFRAC*(D1+D2)
      AMM    = AM(MM)
      GPM(NW)= AMM/3.
      GPM(N2)= GPM(N2)-AMM*BILL/3.
      GPM(N3)= GPM(N3)-AMM*FRED/3.
      AM(MM) = AMM*FRED
      AM(MW) = AMM*BILL
      LAME1(MW) = LAME1(MM)
      LAME2(MW) = LAME2(MM)
      COHES(MW) = COHES(MM)
      TANPHI(MW)= TANPHI(MM)
      TANPSI(MW)= TANPSI(MM)
C-------ESTABLISHMENT OF NEW LINKS ---------------------
      DO 44 J=1,3
      N4     = NAM(MM,J)
      IF (N4 .NE. N2 .AND. N4 .NE. N3) GO TO 45
   44 CONTINUE
   45 N4M(L) = N4
C
      IFL(L)    = 0
      NAM(MM,1) = N4
      NAM(MM,2) = NW
      NAM(MM,3) = N2
      NAM(MW,1) = N4
      NAM(MW,2) = N3
      NAM(MW,3) = NW
      DO 50 I=1,IMAX
      IF (MM .EQ. MAN(N3,I)) GO TO 60
   50 CONTINUE
      STOP
   60 MAN(N3,I) = MW
      DO 70 I=1,IMAX
      IF (MAN(N4,I) .EQ. 0) GO TO 80
   70 CONTINUE
CCCCC PRINT 2100
   80 MAN(N4,I) = MW
      DO 90 I=1,IMAX
   90 MAN(NW,I) = 0
      MAN(NW,1) = MM
      MAN(NW,2) = MW
C-------CORRECT OLD CONTACTS ---------------------------
      DO 100 LC=1,LCONT
      IF (IFG(LC) .EQ. 0) GO TO 100
      IF (N3 .NE. IMD(LC)) GO TO 92
      N2M(LC)    = NW
      MMM(LC)    = IMZ(L)
      GO TO 100
```

```
FORTRAN IV-PLUS V02-04G          11:27:45    29-MAR-78           PAGE 3
CREATE.FTN       /TR:BLOCKS/WR

0090        92 IF (N2 .NE. IMD(LC)) GO TO 100
0091           N3M(LC)    = NW
0092           IMZ(LC)    = MMM(L)
0093       100 CONTINUE
      C
      CCCCC PRINT 2000, L
      CCCCC PRINT 2003
0094           DO 101 N=1,NMAX
      CCCCC PRINT 3003, N,(MAN(N,I),I=1,IMAX)
0095       101 CONTINUE
      CCCCC PRINT 2004, (M,(NAM(M,J),J=1,3),AM(M),M=1,MMAX)
      CCCCC PRINT 2007, (N,GPM(N),N=1,NMAX)
      CCCCC PRINT 2222, (K,IFG(K),IFL(K),IFR(K),IMP(K),IMD(K),N2M(K),N3M(K),
      CCCCC.                MMM(K),IMZ(K),K=1,LCONT)
0096      2222 FORMAT (//' CONTACT LINKS'
         .              /'     L   IFG  IFL  IFR  IMP  IMD  N2M  N3M  MMM  IMZ'
         .              /(1X,10I5))
0097           RETURN
      C
0098      2000 FORMAT (//' **** NEW CONTACT NODE CREATED. CONTACT NO' I4)
0099      2001 FORMAT (//' NODE DATA'//5X,'N',6X,'X',11X,'Y',10X,'XD',
         .            10X,'YD',/(1X,I5,1P4E12.4))
0100      2002 FORMAT (//' ZONE DATA'//5X,'M',5X,'XX',10X,'YY',10X,'XY',
         .            10X,'AM',9X,'LAME1'7X,'LAME2'7X,'COHES'7X,'TANPHI'
         .            6X,'TANPSI'/(I6,1P9E12.4))
0101      2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
         .            5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
         .            5X,'9',5X,'10')
0102      3003 FORMAT (1X,11I6)
0103      2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
         .            5X,'2',5X,'3',5X,'MASS'/(4I6,1PE12.4))
0104      2007 FORMAT (//' GRID POINT MASSES'//5X,'N'4X,'MASS'
         .             /(I6,1PE12.4))
0105      2100 FORMAT ('0NO SPACE TO STORE NEW LINK -- JOB ABORTED')
0106           END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES

$CODE1  002422   649                RW,I,CON,LCL
$VARS   000056    23                RW,D,CON,LCL
$TEMPS  000022     9                RW,D,CON,LCL
CGRID   016374  3710                RW,D,OVR,GBL
COTHR   000110    36                RW,D,OVR,GBL
CPLOT   004570  1212                RW,D,OVR,GBL
CIMPC   001064   282                RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 027102  5921

,LIST.LST/LI:1/-SP=CREATE
```

```
FORTRAN IV-PLUS V02-04G          11:28:12     29-MAR-78            PAGE 1
STRESS.FTN      /TR:BLOCKS/WR

              SUBROUTINE STRESS
        C***************************************************************
        C                                                              *
        C       MOMENTUM BALANCE AT CONTACTS                           *
        C                                                              *
        C***************************************************************
              INCLUDE 'COMMON.FTN'
              REAL LAME1,LAME2
              COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
             .   XNPH(70),YNPH(70),
             .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
             .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
             .   TANPSI(70),MAN(70,10),NAM(70,3)
              COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
             .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
             .   SCALEX,SCALEY
              COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
              COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
             .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
             .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
             .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
        C-------MAIN ITERATION LOOP ----------------------------
              DO 100 M=1,MMAX
              IF (AM(M) .LE. 0) GO TO 100
              XNPH2= XNPH(NAM(M,2))-XNPH(NAM(M,1))
              XNPH3= XNPH(NAM(M,3))-XNPH(NAM(M,1))
              YNPH2= YNPH(NAM(M,2))-YNPH(NAM(M,1))
              YNPH3= YNPH(NAM(M,3))-YNPH(NAM(M,1))
              DET  = XNPH2*YNPH3-YNPH2*XNPH3
              XD2  = XD(NAM(M,2))-XD(NAM(M,1))
              XD3  = XD(NAM(M,3))-XD(NAM(M,1))
              YD2  = YD(NAM(M,2))-YD(NAM(M,1))
              YD3  = YD(NAM(M,3))-YD(NAM(M,1))
        C-------INCREMENTAL STRAINS AND ROTATIONS ----------------
              EDXX = (XD2*YNPH3-XD3*YNPH2)/DET
              EDYY = (YD3*XNPH2-YD2*XNPH3)/DET
              EDXY = 0.5*(XD3*XNPH2-XD2*XNPH3+YD2*YNPH3-YD3*YNPH2)/DET
              RDXY = 0.5*(XD3*XNPH2-XD2*XNPH3-YD2*YNPH3+YD3*YNPH2)/DET
              EXX  = EDXX*DT
              EYY  = EDYY*DT
              EXY  = EDXY*DT
              RXY  = RDXY*DT
              EV   = EXX+EYY
        C-------ELASTIC STRESS INCREMENTS ------------------------
              DXXE = LAME1(M)*EV+2.*LAME2(M)*EXX
              DYYE = LAME1(M)*EV+2.*LAME2(M)*EYY
              DXYE = 2.*LAME2(M)*EXY
        C-------STRESS INCREMENTS ARISING FROM STRESS ROTATION ---
              SDIFF= XX(M)-YY(M)
              DXXR = -RXY*(SDIFF*RXY+2.*XY(M))
              DYYR = -DXXR
              DXYR = RXY*(-2.*RXY*XY(M)+SDIFF)
        C-------VISCOUS STRESS INCREMENT -------------------------
              DXXV = DXXE*BDT
              DYYV = DYYE*BDT
              DXYV = DXYE*BDT
```

```
FORTRAN IV-PLUS V02-04G          11:28:12    29-MAR-78              PAGE 2
STRESS.FTN      /TR:BLOCKS/WR

0038            XXM  = XX(M)+DXXE+DXXR-DXXFV(M)
0039            YYM  = YY(M)+DYYE+DYYR-DYYFV(M)
0040            XYM  = XY(M)+DXYE+DXYR-DXYFV(M)
        C-------YIELD CALCULATIONS ------------------------------
        C-------NEW STRESSES -------------------------------------
0041            XX(M) = XXM+DXXV
0042            YY(M) = YYM+DYYV
0043            XY(M) = XYM+DXYV
0044            DXXFV(M) = DXXV
0045            DYYFV(M) = DYYV
0046            DXYFV(M) = DXYV
0047        100 CONTINUE
0048            RETURN
0049            END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES

$CODE1  001200   320                RW,I,CON,LCL
$VARS   000176    63                RW,D,CON,LCL
$TEMPS  000002     1                RW,D,CON,LCL
CGRID   016374  3710                RW,D,OVR,GBL
COTHR   000110    36                RW,D,OVR,GBL
CPLOT   004570  1212                RW,D,OVR,GBL
CIMPC   001064   282                RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 025760  5624

,LIST.LST/LI:1/-SP=STRESS
```

```
FORTRAN IV-PLUS V02-04G          11:28:27     29-MAR-78            PAGE 1
OUTPUT.FTN       /TR:BLOCKS/WR

0001            SUBROUTINE OUTPUT
          C*****************************************************************
          C                                                                *
          C         CREATION OF OUTPUT FILES                               *
          C                                                                *
          C*****************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .    XNPH(70),YNPH(70),
     *         .    XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .    AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .    TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .    ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .    SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMO(10),IFL(10),IMZ(10),IFG(10),
     *         .    IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .    SINL,SINU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .    FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            COMMON /SHEAR/ FXSUM,FYSUM
          C
0009            IF (MOD(ITER,NPRI)) 10,5,10
0010          5 PRINT 2000, ITER,TIME
0011            PRINT 2001, (N,X(N),Y(N),XD(N),YD(N),N=1,NMAX)
0012            PRINT 2002, (M,XX(M),YY(M),XY(M),AM(M),LAME1(M),LAME2(M),
               .            COHES(M),TANPHI(M),TANPSI(M),M=1,MMAX)
0013         10 IF (MOD(ITER,NPLOT)) 20,15,20
0014         15 NPL = NPL+1
0015            BUF1(NPL) = FYSUM
0016            BUF2(NPL) = TIME
0017            BUF3(NPL) = FXSUM
0018         20 DO 30 I=1,10
0019            IF (ITER .EQ. ITPL(I)) CALL PLOTM
0020         30 CONTINUE
0021            RETURN
0022       2000 FORMAT (////' ITERATION NUMBER ='I5,
               .          /' TIME                ='1PE12.4)
0023       2001 FORMAT (//' NODE DATA'//5X,'N',6X,'X',11X,'Y',10X,'XD',
               .          10X,'YD',/(1X,I5,1P4E12.4))
0024       2002 FORMAT (//' ZONE DATA'//5X,'M',5X,'XX',10X,'YY',10X,'XY',
               .          10X,'AM',9X,'LAME1'7X,'LAME2'7X,'COHES'7X,'TANPHI'
               .          6X,'TANPSI'/(I6,1P9E12.4))
0025            END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	000636	207	RW,I,CON,LCL
$IDATA	000330	108	RW,D,CON,LCL
$VARS	000006	3	RW,D,CON,LCL
CGRID	016374	3710	RW,D,OVR,GBL
COTHR	000110	36	RW,D,OVR,GBL

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FORTRAN IV-PLUS V02-04G          11:28:46    29-MAR-78            PAGE 1
INPUT.FTN        /TR:BLOCKS/WR

0001            SUBROUTINE INPUT
        C**************************************************************
        C                                                             *
        C         GENERATION OF A UNIFORM COLUMNAR MESH               *
        C                                                             *
        C**************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .   XNPH(70),YNPH(70),
     *         .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *         .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .   SINL,SINO,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
        C-------ZONE-NODE LINKS ----------------------------------
0008            NMAX = 4*KTOT+2
0009            MMAX = 4*KTOT
0010            DO 10 K=1,KTOT
0011            KK = 4*(K-1)
0012            MAN(KK+1,1) = KK+1
0013            MAN(KK+1,2) = KK
0014            MAN(KK+2,1) = KK+1
0015            MAN(KK+2,2) = KK+2
0016            MAN(KK+2,3) = KK-1
0017            MAN(KK+2,4) = KK
0018            MAN(KK+3,1) = KK+4
0019            MAN(KK+3,2) = KK+3
0020            MAN(KK+3,3) = KK+2
0021            MAN(KK+3,4) = KK+1
0022            MAN(KK+4,1) = KK+2
0023            MAN(KK+4,2) = KK+3
        C
0024            NAM(KK+1,1) = KK+2
0025            NAM(KK+1,2) = KK+1
0026            NAM(KK+1,3) = KK+3
0027            NAM(KK+2,1) = KK+2
0028            NAM(KK+2,2) = KK+3
0029            NAM(KK+2,3) = KK+4
0030            NAM(KK+3,1) = KK+4
0031            NAM(KK+3,2) = KK+3
0032            NAM(KK+3,3) = KK+6
0033            NAM(KK+4,1) = KK+3
0034            NAM(KK+4,2) = KK+5
0035         10 NAM(KK+4,3) = KK+6
        C
0036            MAN(1,2) = 0
0037            MAN(2,3) = 0
0038            MAN(2,4) = 0
0039            KK = 4*KTOT
```

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FORTRAN IV-PLUS V02-04G          11:28:46     29-MAR-78            PAGE 2
INPUT.FTN         /TR:BLOCKS/WR

              MAN(KK+1,1) = KK
              MAN(KK+2,1) = KK-1
              MAN(KK+2,2) = KK
C-------POSITIONS AND PROPERTIES -------------------------
              K2 = NMAX/2
              DO 20 K1=1,K2
              K  = K1-1
              KK = 2*K
              X(KK+1) = 0
              X(KK+2) = 1.
              Y(KK+1) = FLOAT(K2-K1)
              Y(KK+2) = FLOAT(K2-K1)
C
              XD(KK+1) = 0
              YD(KK+1) = 0
              XD(KK+2) = 0
           20 YD(KK+2) = 0
C
              DO 30 M=1,MMAX
              XX(M) = 0
              YY(M) = 0
              XY(M) = 0
              RHO(M) = 10.
              LAME1(M) = 3567.1
              LAME2(M) = 343.14
              COHES(M) = 0
              TANPHI(M)= 0
           30 TANPSI(M)= 0
C
              PRINT 2001, (N,X(N),Y(N),XD(N),YD(N),N=1,NMAX)
              PRINT 2002, (M,XX(M),YY(M),XY(M),RHO(M),LAME1(M),LAME2(M),
     .                  COHES(M),TANPHI(M),TANPSI(M),M=1,MMAX)
              PRINT 2003, (N,(MAN(N,I),I=1,IMAX),N=1,NMAX)
              PRINT 2004, (M,(NAM(M,J),J=1,3),M=1,MMAX)
              RETURN
         2001 FORMAT (//' NODE DATA'//5X,'N',6X,'X',11X,'Y',10X,'XD',
     .                10X,'YD',/(1X,I5,1P4E12.4))
         2002 FORMAT (//' ZONE DATA'//5X,'M',5X,'XX',10X,'YY',10X,'XY',
     .                10X,'AM',9X,'LAME1'7X,'LAME2'7X,'COHES'7X,'TANPHI'
     .                6X,'TANPSI'/(I6,1P9E12.4))
         2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
     .                5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
     .                5X,'9',5X,'10',/(5I6))
         2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
     .                5X,'2',5X,'3',/(4I6))
              END
```

PROGRAM SECTIONS

NAME	SIZE		ATTRIBUTES
$CODE1	001552	437	RW,I,CON,LCL
$PDATA	000010	4	RW,D,CON,LCL
$IDATA	000460	152	RW,D,CON,LCL
$VARS	000020	8	RW,D,CON,LCL

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FORTRAN IV-PLUS V02-04G          11:29:11    29-MAR-78            PAGE 1
PLOTM.FTN        /TR:BLOCKS/WR

              SUBROUTINE PLOTM
      C**************************************************************
      C                                                             *
      C         PREPARATION OF MESH PLOTS                           *
      C                                                             *
      C**************************************************************
              INCLUDE 'COMMON.FTN'
              REAL LAME1,LAME2
              COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
             .   XNPH(70),YNPH(70),
             .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
             .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
             .   TANPSI(70),MAN(70,10),NAM(70,3)
              COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
             .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
             .   SCALEX,SCALEY
              COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
              COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
             .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
             .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
             .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
              CALL PLOT(11.,0.,-3)
      C
              DO 20 M=1,MMAX
              IF (AM(M) .EQ. 0) GO TO 20
              AX = SCALEX*X(NAM(M,3))
              AY = SCALEY*Y(NAM(M,3))
              CALL PLOT(AX,AY,3)
              DO 10 J=1,3
              AX = SCALEX*X(NAM(M,J))
              AY = SCALEY*Y(NAM(M,J))
              CALL PLOT(AX,AY,2)
           10 CONTINUE
           20 CONTINUE
      C-------PRINT RESULTS ------------------------------------
              PRINT 2003
              DO 101 N=1,NMAX
              PRINT 3003, N,(MAN(N,I),I=1,IMAX)
          101 CONTINUE
              PRINT 2004, (M,(NAM(M,J),J=1,3),AM(M),M=1,MMAX)
              PRINT 2007, (N,GPM(N),N=1,NMAX)
              PRINT 2222, (K,IFG(K),IFL(K),IFR(K),IMP(K),IMD(K),N2M(K),N3M(K),
             .            MMM(K),IMZ(K),K=1,LCONT)
         2222 FORMAT (//' CONTACT LINKS'
             .          /'    L   IFG  IFL  IFR  IMP  IMD  N2M  N3M  MMM  IMZ'
             .          /(1X,10I5))
         2001 FORMAT (//' NODE DATA'//5X,'N',6X,'X',11X,'Y',10X,'XD',
             .          10X,'YD',/(1X,I5,1P4E12.4))
         2002 FORMAT (//' ZONE DATA'//5X,'M',5X,'XX',10X,'YY',10X,'XY',
             .          10X,'AM',9X,'LAME1'7X,'LAME2'7X,'COHES'7X,'TANPHI'
             .          6X,'TANPSI'/(I6,1P9E12.4))
         2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
             .          5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
             .          5X,'9',5X,'10')
         3003 FORMAT (1X,11I6)
         2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
```

```
FORTRAN IV-PLUS V02-04G          11:29:11    29-MAR-78              PAGE 2
PLOTM.FTN        /TR:BLOCKS/WR

                .          5X,'2',5X,'3',5X,'MASS'/(4I6,1PE12.4))
0033       2007 FORMAT (//' GRID POINT MASSES'//5X,'N'4X,'MASS'
                .          /(I6,1PE12.4))
0034            RETURN
0035            END

PROGRAM SECTIONS

 NAME       SIZE                     ATTRIBUTES

$CODE1   001152    309               RW,I,CON,LCL
$PDATA   000024     10               RW,D,CON,LCL
$IDATA   000472    157               RW,D,CON,LCL
$VARS    000022      9               RW,D,CON,LCL
$TEMPS   000002      1               RW,D,CON,LCL
CGRID    016374   3710               RW,D,OVR,GBL
COTHR    000110     36               RW,D,OVR,GBL
CPLOT    004570   1212               RW,D,OVR,GBL
CIMPC    001064    282               RW,D,OVR,GBL

TOTAL SPACE ALLOCATED = 026274  5726

,LIST.LST/LI:1/-SP=PLOTM
```

```
FORTRAN IV-PLUS V02-04G          11:29:36    29-MAR-78           PAGE 1
MESH.FTN         /TR:BLOCKS/WR

      SUBROUTINE MESH
C*************************************************************
C                                                            *
C      GENERATION OF ARBITRARY MESHES                        *
C                                                            *
C*************************************************************
      BYTE LIST,LENG,IFLA,LWAIT
      INCLUDE 'COMMON.FTN'
      REAL LAME1,LAME2
      COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     .   XNPH(70),YNPH(70),
     .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     .   TANPSI(70),MAN(70,10),NAM(70,3)
      COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     .   SCALEX,SCALEY
      COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
      COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
      COMMON /CNICE/ NTIMES,FACTOR,IBOUND(100)
      DIMENSION LIST(20,20),LENG(20),IFLA(20),LWAIT(20),
     .   LTEMPA(20),LTEMPB(20)
      DATA NTIMES,FACTOR /10,0.5/
C
C-----READ NUMBER OF BLOCKS AND SCALE FOR PLOTTING
      READ  1000, NBLOCK
      PRINT 2000, NBLOCK
      READ  1001, SCALE
      PRINT 2001, SCALE
      SCALEX = SCALE
      SCALEY = SCALE
      MMAX   = 0
      NMAX   = 0
      IMAX   = 10
C
      DO 100 NB=1,NBLOCK
C-------READ NUMBER OF CORNERS AND THEIR COORDINATES
      READ  1000, NCORN
      PRINT 2002, NCORN
      READ  1002, (LIST(1,I),X(I),Y(I),I=1,NCORN)
      PRINT 2005, (I,LIST(1,I),X(I),Y(I),I=1,NCORN)
C-------INITIALIZATIONS
      NMAX = NMAX+NCORN
      NW   = 0
      DO 5 I=2,20
      IFLA(I) = 0
      LENG(I) = 0
      LWAIT(I)= 0
      DO 5 J=1,20
    5 LIST(I,J) = 0
      IF (NCORN .GT. 3) GO TO 10
C-------CASE OF TRIANGULAR BLOCK
      MMAX = MMAX+1
```

```
              AM(MMAX) = 1.
              DO 6 I=1,3
            6 NAM(MMAX,I) = LIST(1,I)
              GO TO 100
C-------FORM INITIAL LIST
           10 IFLA(1)  = 1
              NLIST = 1
              NSPLT = 1
              LENG(NSPLT) = NCORN
C-------FIND THE TWO CLOSEST NON CONTIGUOUS CORNERS---------
C-----------------------------------------------------------
           22 DISM = 1.E10
              NCL  = LENG(NSPLT)
              NLIM = NCL-2
C
              DO 30 IX=1,NLIM
              II = IX+2
              IP = LIST(NSPLT,IX)
              DO 30 JX=II,NCL
              JP = LIST(NSPLT,JX)
              DISTS = (X(IP)-X(JP))**2+(Y(IP)-Y(JP))**2
              PRINT 3010,IP,JP,DISTS,DISM
         3010 FORMAT('IP,JP,DISTS,DISM'2I3,1P2E12.4)
              IF (DISTS .GT. DISM) GO TO 30
              IF (IX .EQ.1 .AND. JX .EQ. NCL) GO TO 30
              IM    = IX
              JM    = JX
              PRINT 3000,IM,JM
         3000 FORMAT(' IM,JM'2I3)
C-------FORM FIRST NEW LIST
              DO 40 I=1,IM
           40 LTEMPA(I) = LIST(NSPLT,I)
              DO 50 I=JM,NCL
              II = I+IM-JM+1
           50 LTEMPA(II)= LIST(NSPLT,I)
              LA = IM+NCL-JM+1
              DO 55 I=LA,19
           55 LTEMPA(I+1) = 0
              PRINT 3001,(LTEMPA(I),I=1,6)
         3001 FORMAT(' LIST   '6I3)
C-------CHECK AREA
              AR = 0
              DO 56 I=2,LA
              N1 = LTEMPA(I-1)
              N2 = LTEMPA(I)
           56 AR = AR+(Y(N1)+Y(N2))*(X(N1)-X(N2))
              N1 = LTEMPA(LA)
              N2 = LTEMPA(1)
              AR = AR+(Y(N1)+Y(N2))*(X(N1)-X(N2))
              ARC= 0.1*DISTS
              IF (AR .GT. ARC) GO TO 59
              GO TO 30
           59 CONTINUE
C-------FORM SECOND NEW LIST
              DO 60 I=IM,JM
              II = I-IM+1
```

```
     60 LTEMPB(I1) = LIST(NSPLT,I)
        DO 70 I=I1,19
     70 LTEMPB(I+1) = 0
        PRINT 3001,(LTEMPB(I),I=1,6)
        LB = JM-IM+1
C-------CHECK AREA
        AR = 0
        DO 66 I=2,LB
        N1 = LTEMPB(I-1)
        N2 = LTEMPB(I)
     66 AR = AR+(Y(N1)+Y(N2))*(X(N1)-X(N2))
        N1 = LTEMPB(LB)
        N2 = LTEMPB(1)
        AR = AR+(Y(N1)+Y(N2))*(X(N1)-X(N2))
        IF (AR .LT. ARC) GO TO 30
        DISM = DISTS
        IMIN = IM
        JMIN = JM
        PRINT 4000,IMIN,JMIN,DISM
   4000 FORMAT(' IMIN,JMIN,DISM' 2I3,1PE12.4)
     30 CONTINUE
C
C-------FIND AN UNUSED LIST
        DO 35 I=1,NLIST
        IF (IFLA(I) .NE. 0) GO TO 35
        NN     = I
        GO TO 36
     35 CONTINUE
        NLIST = NLIST+1
        NN    = NLIST
     36 IFLA(NN) = 1
C-------FORM FINAL LISTS
        DO 41 I=1,IMIN
     41 LIST(NN,I) = LIST(NSPLT,I)
        DO 42 I=JMIN,NCL
        I1 = I+IMIN-JMIN+1
     42 LIST(NN,I1)= LIST(NSPLT,I)
        LENG(NN) = IMIN+NCL-JMIN+1
        DO 43 I=LENG(NN),19
     43 LIST(NN,I+1) = 0
C
        DO 44 I=IMIN,JMIN
        I1 = I-IMIN+1
     44 LIST(NSPLT,I1) = LIST(NSPLT,I)
        LENG(NSPLT) = JMIN-IMIN+1
        DO 45 I=LENG(NSPLT),19
     45 LIST(NSPLT,I+1) = 0
C-------CASE OF TRIANGULAR LISTS
        IF (LENG(NN) .GT. 3) GO TO 57
        MMAX = MMAX+1
        AM(MMAX) = 1.
        NAM(MMAX,1) = LIST(NN,1)
        NAM(MMAX,2) = LIST(NN,2)
        NAM(MMAX,3) = LIST(NN,3)
        IFLA(NN) = 0
        GO TO 58
```

```
   57 NW = NW+1
      LWAIT(NW) = NN
C
   58 IF (LENG(NSPLT) .GT. 3) GO TO 22
      MMAX = MMAX+1
      AM(MMAX) = 1.
      NAM(MMAX,1) = LIST(NSPLT,1)
      NAM(MMAX,2) = LIST(NSPLT,2)
      NAM(MMAX,3) = LIST(NSPLT,3)
      IFLA(NSPLT) = 0
C--------GET NEXT LIST FOR SPLITTING IT
      IF (NW .LE. 0) GO TO 100
      NSPLT = LWAIT(NW)
      NW = NW-1
      GO TO 22
  100 CONTINUE
C--------GENERATE MAN (ZONES AROUND EACH NODE)
      DO 108 M=1,MMAX
      DO 108 J=1,3
      N =NAM(M,J)
      DO 106 I=1,IMAX
      IF (MAN(N,I) .NE. 0) GO TO 106
      MAN(N,I) = M
      GO TO 108
  106 CONTINUE
      PRINT 5000
 5000 FORMAT(' NO SPACE FOR THIS LINK - ABORTED')
      STOP
  108 CONTINUE
C--------PRINT RESULTS
      PRINT 2003, (N,(MAN(N,I),I=1,IMAX),N=1,NMAX)
      PRINT 2004, (M,(NAM(M,J),J=1,3),M=1,MMAX)
C--------REDUCE ZONE SIZE AND IMPROVE MESH
      CALL REDUCE
C     CALL DIAG
      IF (NTIMES .GT. 0) CALL NICE
C--------PLOT MESH
      CALL PLOTST(0.025,'CM')
      CALL PLOTM
      CALL PLOTND
      RETURN
C
 1000 FORMAT(8I10)
 1001 FORMAT(8F10.0)
 1002 FORMAT(I10,2F10.0)
 2000 FORMAT(//' NUMBER OF BLOCKS       ='I3)
 2001 FORMAT(//' SCALE FOR PLOTTING     ='1PE12.4)
 2002 FORMAT(//' NUMBER OF CORNERS      ='I3)
 2005 FORMAT(//' CORNER COORDINATES'
     .        /'   SEQ.NO.  COR.NO.         X            Y'
     .        /(4X,I3,5X,I3,5X,1P2E12.4))
 2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
     .        5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
     .        5X,'9',5X,'10',/(11I6))
 2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
     .        5X,'2',5X,'3',/(4I6))
```

```
              SUBROUTINE REDUCE
        C***************************************************************
        C                                                              *
        C       CLOSE MESH TO DESIRED DENSITY                          *
        C                                                              *
        C***************************************************************
              INCLUDE 'COMMON.FTN'
              REAL LAME1,LAME2
              COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
             .   XNPH(70),YNPH(70),
             .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
             .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
             .   TANPSI(70),MAN(70,10),NAM(70,3)
              COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
             .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
             .   SCALEX,SCALEY
              COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
              COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
             .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
             .   STNL,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
             .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
              COMMON /CNICE/ NTIMES,FACTOR,IBOUND(100)
              READ  1001, AMAXL
              PRINT 2000, AMAXL
              AMAXS = AMAXL*AMAXL
              M1A  = 0
        C-------MAIN ITERATION LOOP -------------------------------------
            1 M1A = M1A+2
              IF (M1A .GT. MMAX) GO TO 501
              N1  = NAM(M1A,1)
              N2  = NAM(M1A,2)
              N3  = NAM(M1A,3)
        C
              D1S = (X(N1)-X(N2))**2+(Y(N1)-Y(N2))**2
              D2S = (X(N2)-X(N3))**2+(Y(N2)-Y(N3))**2
              D3S = (X(N3)-X(N1))**2+(Y(N3)-Y(N1))**2
        C
              IF (AMAXS .GE. AMAX1(D1S,D2S,D3S)) GO TO 500
              IF (D1S .GE. AMAX1(D2S,D3S)) GO TO 10
              IF (D2S .GE. AMAX1(D1S,D3S)) GO TO 20
              NA  = N3
              NB  = N1
              NN1 = N2
              GO TO 30
           10 NA  = N1
              NB  = N2
              NN1 = N3
              GO TO 30
           20 NA  = N2
              NB  = N3
              NN1 = N1
        C
           30 DO 42 I=1,IMAX
              M3A = MAN(NA,I)
              IF (M3A .EQ. 0) GO TO 42
              IF (M3A .EQ. M1A) GO TO 42
```

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FORTRAN IV-PLUS V02-04G         11:31:30    29-MAR-78             PAGE 2
REDUCE.FTN       /TR:BLOCKS/WR

          DO 40 J=1,IMAX
          IF (M3A .NE. MAN(NB,J)) GO TO 40
          M2A = M3A
          GO TO 50
       40 CONTINUE
       42 CONTINUE
C
          IF2 = 0
          GO TO 60
       50 IF2 = 1
C
          DO 55 I=1,3
          IF (NA .NE. NAM(M2A,I)) GO TO 55
          I2  = I+1
          IF (I2 .EQ. 4) I2=1
          NN2 = NAM(M2A,I2)
       55 CONTINUE
C-------REORGANISE LINKS IN THE SAFE SIDE
       60 NMAX = NMAX+1
          IBOUND(NMAX) = IF2
          X(NMAX) = 0.5*(X(NA)+X(NB))
          Y(NMAX) = 0.5*(Y(NA)+Y(NB))
          MMAX = MMAX+1+IF2
          AM(MMAX) = 1.
          AM(MMAX-IF2) = 1.
C
          DO 70 I=1,IMAX
          IF (MAN(NB,I) .NE. M1A) GO TO 70
          MAN(NB,I) = MMAX
          GO TO 80
       70 CONTINUE
C
       80 DO 90 I=1,IMAX
          IF (MAN(NN1,I) .NE. 0) GO TO 90
          MAN(NN1,I) = MMAX
          GO TO 100
       90 CONTINUE
C
      100 MAN(NMAX,1) = MMAX
          MAN(NMAX,2) = M1A
C
          DO 110 I=1,3
          IF (NAM(M1A,I) .EQ. NB) NAM(M1A,I)=NMAX
      110 CONTINUE
C
          NAM(MMAX,1) = NB
          NAM(MMAX,2) = NN1
          NAM(MMAX,3) = NMAX
C
C-------REORGANISE LINKS ON THE OTHER SIDE IF REQUIRED
          IF (IF2 .EQ. 0) GO TO 500
          MMA1 = MMAX-1
C
          MAN(NMAX,3) = M2A
          MAN(NMAX,4) = MMA1
C
```

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FORTRAN IV-PLUS V02-04G          11:31:30    29-MAR-78             PAGE 3
REDUCE.FTN       /TR:BLOCKS/WR

0083               DO 120 I=1,IMAX
0084               IF (MAN(NB,I) .NE. M2A) GO TO 120
0085               MAN(NB,I) = MMA1
0086               GO TO 130
0087           120 CONTINUE
             C
0088           130 DO 140 I=1,IMAX
0089               IF (MAN(NN2,I) .NE. 0) GO TO 140
0090               MAN(NN2,I) = MMA1
0091               GO TO 150
0092           140 CONTINUE
             C
0093           150 DO 160 I=1,3
0094               IF (NAM(M2A,I) .EQ. NB) NAM(M2A,I)=NMAX
0095           160 CONTINUE
             C
0096               NAM(MMA1,1) = NB
0097               NAM(MMA1,2) = NMAX
0098               NAM(MMA1,3) = NN2
             C
0099           500 GO TO 1
             C
0100           501 DO 510 M=1,MMAX
0101               N1  = NAM(M,1)
0102               N2  = NAM(M,2)
0103               N3  = NAM(M,3)
0104               D1S = (X(N1)-X(N2))**2+(Y(N1)-Y(N2))**2
0105               D2S = (X(N2)-X(N3))**2+(Y(N2)-Y(N3))**2
0106               D3S = (X(N3)-X(N1))**2+(Y(N3)-Y(N1))**2
0107               IF (AMAX1(D1S,D2S,D3S) .LE. AMAXS) GO TO 510
0108               M1A = MOD(M1A,2)-1
0109               GO TO 1
0110           510 CONTINUE
             C
0111               PRINT 2003, (N,(MAN(N,I),I=1,IMAX),N=1,NMAX)
0112               PRINT 2004, (M,(NAM(M,J),J=1,3),M=1,MMAX)
0113               RETURN
0114          1001 FORMAT(8F10.0)
0115          2000 FORMAT(' MAXIMUM EDGE LENGTH ALLOWED ='1PE12.4)
0116          2003 FORMAT (//' ZONES SURROUNDING EACH NODE'//5X,'N',5X,'1',
                  .        5X,'2',5X,'3',5X,'4',5X,'5',5X,'6',5X,'7',5X,'8',
                  .        5X,'9',5X,'10',/(11I6))
0117          2004 FORMAT (//' NODES SURROUNDING EACH ZONE'//5X,'M',5X,'1',
                  .        5X,'2',5X,'3',/(4I6))
0118               END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES

$CODE1   003126    811              RW,I,CON,LCL
$IDATA   000322    105              RW,D,CON,LCL
$VARS    000066     27              RW,D,CON,LCL
$TEMPS   000022      9              RW,D,CON,LCL
CGRID    016374   3710              RW,D,OVR,GBL
```

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FORTRAN IV-PLUS V02-04G          11:32:37     29-MAR-78              PAGE 1
NICE.FTN          /TR:BLOCKS/WR

0001            SUBROUTINE NICE
          C*************************************************************
          C                                                             *
          C        SIMPLE MESH OPTIMIZATION                             *
          C                                                             *
          C*************************************************************
0002            INCLUDE 'COMMON.FTN'
0003 *          REAL LAME1,LAME2
0004 *          COMMON /CGRID/ X(70),Y(70),XD(70),YD(70),GPM(70),
     *         .   XNPH(70),YNPH(70),
     *         .   XX(70),YY(70),XY(70),DXXFV(70),DYYFV(70),DXYFV(70),
     *         .   AM(70),RHO(70),LAME1(70),LAME2(70),COHES(70),TANPHI(70),
     *         .   TANPSI(70),MAN(70,10),NAM(70,3)
0005 *          COMMON /COTHR/ DT,NITER,ARAT,GRAV,ITER,NMAX,MMAX,IMAX,TIME,
     *         .   ZERO,NPRI,LCONT,IFLAG,KTOT,NBUF,NPL,NPLOT,ITPL(10),
     *         .   SCALEX,SCALEY
0006 *          COMMON /CPLOT/ BUF1(202),BUF2(202),BUF3(202)
0007 *          COMMON /CIMPC/ IMP(10),IMD(10),IFL(10),IMZ(10),IFG(10),
     *         .   IFR(10),N2M(10),N3M(10),MMM(10),N4M(10),TOLC(10),
     *         .   STNC,STNU,STSH,XMU,TOL,BDT,BDT1,CON1,CON2,TFRAC,
     *         .   FN(10),FS(10),DRN(10),DRS(10),DRST(10),XNC(10),YNC(10),DN
0008            COMMON /CNICE/ NTIMES,FACTOR,IBOUND(100)
          C
0009            DO 80 NTIME=1,NTIMES
0010            DO 90 N=1,NMAX
0011            IF (IBOUND(N) .EQ. 0) GO TO 90
0012            XSUM = 0
0013            YSUM = 0
0014            ANUM = 0
          C
0015            DO 15 I=1,IMAX
0016            M = MAN(N,I)
0017            IF (M .EQ. 0) GO TO 20
          C
0018            DO 10 J=1,3
0019            IF (NAM(M,J) .NE. N) GO TO 10
0020            JM = J+1
0021            IF (JM .EQ. 4) JM=1
0022            XSUM = XSUM+X(NAM(M,JM))
0023            YSUM = YSUM+Y(NAM(M,JM))
0024            ANUM = ANUM+1.
0025            PRINT 1000,N,I,M,J,JM,NAM(M,JM),ANUM,XSUM,YSUM,FACTOR,X(N),Y(N)
0026       1000 FORMAT(1X,6I4,6F6.2)
0027         10 CONTINUE
0028         15 CONTINUE
0029         20 X(N) = FACTOR*X(N)+(1.-FACTOR)*XSUM/ANUM
0030            Y(N) = FACTOR*Y(N)+(1.-FACTOR)*YSUM/ANUM
0031         90 CONTINUE
0032         80 CONTINUE
0033            RETURN
0034            END

PROGRAM SECTIONS

 NAME        SIZE                   ATTRIBUTES
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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Maini, Tidu
Computer modelling of jointed rock masses / by Tidu Maini ... [et al.], Dames and Moore, Los Angeles, Calif. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
iii, 396 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; N-78-4)
Prepared for Defense Nuclear Agency, Washington, D. C., and Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACA39-77-C-0004.

1. Computer programs. 2. Computerized models. 3. Dynamic loads. 4. Jointed rock. 5. Rock deformation. 6. Rock masses. I. Dames and Moore. II. Defense Nuclear Agency. III. United States. Army. Corps of Engineers. IV. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; N-78-4.
TA7.W34 no.N-78-4

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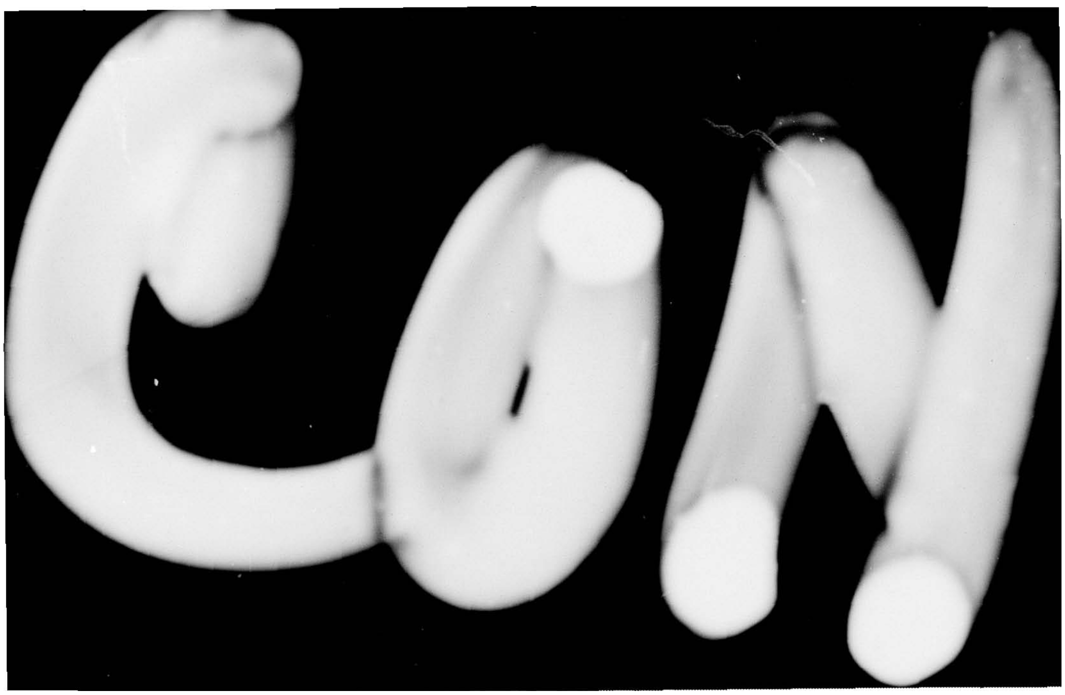
CON

AD-A061 658 DAMES AND MOORE LOS ANGELES CA F/G 8/7
COMPUTER MODELING OF JOINTED ROCK MASSES.(U)
AUG 78 P CUNDALL, J MARTI, P BERESFORD DACA39-77-C-0004
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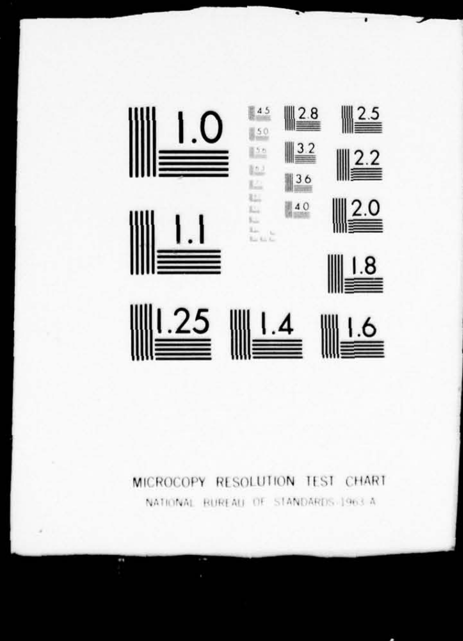

SUPPLEMENTARY

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DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
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VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESSP

31 January 1979

Errata Sheet

No. 1

COMPUTER MODELLING OF JOINTED ROCK MASSES

Technical Report N-78-4
August 1978

1. The names of the authors on both the cover and in block 7 of the Form 1473 should read:

   Peter Cundall, Joaquin Marti, Peter Beresford, Nigel Last, Margaret Asgian

2. The first two lines of the facsimile catalog card, the page facing page 396, should read:

   Cundall, Peter
   Computer modelling of jointed rock masses / by Peter Cundall...